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Interim Storage of Radioactive Waste Packages

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1998

INTERIM STORAGE
OF RADIOACTIVE
WASTE PACKAGES

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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FOREWORD

Nuclear power production and the use of radioactive materials and ionizing radiation in industry, agriculture, medicine and research generate radioactive wastes. These wastes must be safely managed at all stages prior to and including ultimate safe disposal. Storage is an integral part of the waste management process. While the storage of conditioned waste is normally described as interim storage, for some Member States this will probably be fairly long term, even to the point of de facto disposal. Somewhere between ten and fifty years will most likely be required for storage until a repository can be constructed and licensed, or until radioactivity has decayed to a sufficiently low level for disposal as cleared waste.

Since the storage of radioactive waste had not been adequately covered in technical publications of the International Atomic Energy Agency, it was decided to review past and current experience and prepare a report to provide technical guidance to Member States on safe and economic methods for storage of radioactive waste packages.

This report covers all the principal aspects of production and interim storage of radioactive waste packages. The latest design solutions of waste storage facilities and the operational experiences of developed countries are described and evaluated in order to assist developing Member States in decision making and design and construction of their own storage facilities. The report provides a source of technical information for all organizations involved in the waste management process, including waste generators, designers and operators of conditioning and storage facilities, and national regulatory bodies.

The original draft report was prepared by five consultants: H. Brücher, Forschungszentrum Jülich GmbH (Germany), N. Dellero, NUSYS–Transnucléaire (France), R. Reynders, Belgoprocess (Belgium), P. Richards, British Nuclear Fuels plc (United Kingdom), and R. Stupka, Los Alamos National Laboratory (USA). The Technical Committee meeting (TCM), at which the report was reviewed and much additional information contributed, was attended by 19 experts and held in Vienna from 23 to 27 September 1996. After the TCM the same group of consultants, except R. Reynders, finalized the report.

The IAEA is grateful to those who have taken part in the preparation of this report, particularly the consultants and P. Risoluti (Italy), Chairman of the TCM. The IAEA officer responsible for the report was V.S. Tsyplenkov from the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

A waste management system is developed using an approach that addresses the safety of all the steps and operations involved as a whole, rather than the safety of each separate step. The basic steps in radioactive waste management, depending on the type of waste, are pretreatment, treatment, conditioning, storage and disposal. The steps are interrelated. Each step must be carefully designed and performed, and the effects of future radioactive waste management activities, particularly disposal, taken into account when any separate radioactive waste management activity is being considered. Conditioning of radioactive waste involves those operations that transform radioactive waste into a form suitable for handling, transport and disposal. However, if for some reason disposal of waste packages cannot be made immediately after conditioning (e.g. if a disposal facility is not available or if radioactivity in waste packages must decay to lower levels), interim storage of waste packages is required and must be arranged in such a way as to ensure the integrity of radioactive waste packages and their suitability for further disposal after retrieval from a storage facility.

The core of the waste management system is the technology which is applied to the waste from generation to disposal. Waste management technology has received considerable attention in Member States in view of the importance of the link between nuclear power and nuclear applications on one hand, and, on the other, the safe management of radioactive waste resulting from the use of nuclear energy. Application of this technology is important to ensure radiological safety for workers and the public and to avoid accidents or unnecessary releases of radionuclides associated with radioactive waste. In countries with a developed nuclear industry, qualified conditioning processes exist. Wastes conditioned by these processes are normally qualified for long term safety and integrity. Usually, processes that use a matrix are considered as definitive for the waste form, and further conditioning only involves packaging.

To date, most aspects of waste processing and disposal of low, intermediate and high level radioactive waste have been addressed in various IAEA publications. However, the subject of radioactive waste storage has not been adequately addressed as an integral part of the waste management system ultimately leading to disposal. Also, the integrated requirements of the disposal system that result in the development of waste package criteria and specifications, and the impact of interim storage on the waste as an engineered system, have largely been ignored in the literature.

1.2. OBJECTIVE

The objective of this report is to provide Member States with guidance on various technological aspects of radioactive waste package storage as part of the entire waste management process. Current practices for radioactive waste storage, related to the safety principles applied both to packages and storage facilities, are reviewed. The report also differentiates between the roles of waste acceptance criteria and waste specifications, and indicates how they must interact with container and facility design parameters to ensure safety.

The actions required before, during and after interim storage are summarized, and their interrelationship within the comprehensive waste management system is established. Examples of waste packages, waste storage practices and storage facilities in selected Member States are presented that illustrate proved and recommended designs and practices to reinforce the principles and techniques discussed in the text.

1.3. SCOPE

This report is applicable to any category of radioactive waste package prepared for interim storage, including conditioned spent fuel, high level waste and sealed radiation sources. Short periods of storage for processing purposes and area storage of low and intermediate level waste (LILW) awaiting transport to the available final disposal facility is beyond the scope of this report.

Obviously, national policy decisions regarding the nuclear energy programme influence the waste management strategy. For instance, some Member States reprocess spent fuel while others place it in storage as waste awaiting disposal. Waste packages prepared in conformity with an established set of acceptance criteria for disposal, as well as packages with less well defined specifications, are discussed. The period of storage assumed in the report to be applicable for interim storage ranges from several years to about 50 years. Technical features and quality control requirements established for the waste packages and storage system should be designed to match the expected time of storage.

1.4. STRUCTURE

The report consists of eight sections, including a conclusion.

Section 2 presents the safety principles and requirements for storage of waste packages. It begins with a brief summary of the basic safety principles that apply to all activities in the waste management system, and proceeds to a discussion of requirements for waste packages arising from several different sources.

Section 3 describes treatment and conditioning methods for the main categories of radioactive waste that may require storage. It includes a brief overview of conditioning processes and presents representative samples of waste packages from several Member States.

Section 4 addresses the three major types of storage facility now in use by Member States, and relates their experience in interim storage by presenting examples of existing interim storage facilities for LILW, spent fuel and high level waste (HLW).

Section 5 is based on the operational experience of Member States in waste storage operations including control of storage conditions, surveillance of waste packages and observation of the behaviour of waste packages during storage.

Section 6 addresses the issue of retrieval of waste packages from storage facilities. The functions of record keeping, package testing, inspection, and general management options are discussed.

Section 7 recommends technical and administrative measures that will ensure optimal performance of waste packages subject to various periods of interim storage.

Section 8 concludes with international experience in designing and operating storage facilities.

The Appendix gives details of storage facilities in selected Member States.

2. SAFETY PRINCIPLES AND REQUIREMENTS FOR WASTE PACKAGE STORAGE

2.1. SAFETY PRINCIPLES

The design and operation of storage facilities in each Member State must comply with the basic safety principles set up in the IAEA Safety Standard, “International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources” [1] and the Safety Fundamentals, “The Principles of Radioactive Waste Management” [2]. The former is based on guidelines issued by the International Commission on Radiological Protection (ICRP) in Publication 46 [3] and Publication 60 [4]. Together, these principles and guidelines dictate the behaviour of the national waste management system, of which the storage step is an integral part. More specifically, storage of radioactive waste, like all other steps of waste management, must comply with the three main principles of radiation protection [1]:

- The normal exposure of employees and the public must be restricted and must not exceed specified dose limits;

- The practice must be justified in terms of the risk incurred versus the benefit to society;
- The practice, while keeping exposures as low as reasonably achievable (ALARA), must be optimized to provide maximum benefit for the cost incurred.

Additional waste management principles are also important. Briefly, these basic principles [2], as applied to the storage of radioactive waste, include:

- Protection beyond national borders;
- Management of the storage operation within, and compatible with, the existing legal framework;
- Avoidance of shifting the burden of storage and ultimate disposal of the waste to future generations;
- Minimal generation of radioactive waste, designed to facilitate its management by incorporating principles such as recycle/reuse, selection and control of radioactive materials, and design of facilities with decommissioning in mind;
- Safety of the storage facility;
- Protection of the environment from the storage operation.

The national regulatory authority may place additional constraints on the waste management process with regard to storage. For instance, requirements for managing radioactive wastes mixed with hazardous chemical or biological substances may impose additional constraints on interim storage, including facility design and administrative controls that govern waste handling.

National policies in nuclear energy generation and applications of radionuclides in research, medicine and industry greatly affect the amount and characteristics of waste requiring management as well as the way it must be managed. A typical example is the decision of a Member State whether or not to reprocess spent nuclear fuel.

A consistent approach should be taken by the national authority regarding the safety of all nuclear facilities within its borders in order to ensure compliance with international safety standards. Operation of any facility, including one for storage, should be supported by a systematic safety assessment that addresses: (a) potential accidents and measures taken to limit their consequences (if necessary); (b) site selection and other design features as they relate to safety; (c) provisions for surveillance and periodic reassessment of the safety of the facility. In particular, a principle of nuclear safety in relation to a single waste package and the storage facility design must be complied with. Industrial safety standards must also be incorporated in the design and operation of storage facilities.

Finally, the storage facility must function as an integrated part of the whole waste management system. To assess compliance of the storage facility with the basic safety principles and objectives, a licensing process including safety and environmental impact assessments must be part of the waste management system.

2.2. REQUIREMENTS FOR WASTE PACKAGES

A wide variety of waste packages are used in Member States to meet the needs of the nuclear industry and research. Many specialized types are designed and manufactured with the needs of a specific user in mind; however, others, such as the Type A 200 L drum package, must meet the needs of a wide variety of users. The package manufacturer should ensure that the waste container and waste form are able to combine reliably to form a waste package that meets a defined set of technical requirements for various potential waste management stages including storage, transport and disposal.

Radioactive waste may exist in several forms when it passes through the treatment and conditioning processes. It may exist sequentially as raw, treated, immobilized and fully conditioned waste. While in storage it should be expected to retain its form and suitability for transport and disposal for up to 50 years without subsequent reconditioning. This is accomplished through the interaction of three sets of criteria: the waste acceptance criteria (WAC), the waste form and container specifications, and the design and operating requirements of the storage facility.

2.2.1. Waste form, container and waste package

The waste form is the waste in its physical and chemical form after treatment and/or immobilization (resulting in a solid product) prior to packaging [5]. Immobilization of waste, i.e. the conversion of a waste into a waste form by solidification, embedding or encapsulation, may be required, depending on the type of waste. Waste immobilization reduces the potential for migration or dispersion of radionuclides during handling, transport, storage and disposal. Examples of waste as they may arise, for instance, from the operation of radiochemical laboratories, are given in Fig. 1 for non-immobilized waste and in Fig. 2 for immobilized waste.

The container is the vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal. It is essential that the quality of the container is not detrimental to the safety of handling, transport, storage and disposal when exposed to a corrosive environment. The container must also retain its integrity in an accident scenario. For LILW, detailed descriptions of containers are given in Ref. [6].

Waste containers may be designed for relatively short or long lives, depending on their role in limiting or preventing the release of radionuclides in a disposal system for a limited time span. Regardless of the intended life in the disposal facility,

FIG. 1. Non-immobilized solid waste (glassware, evaporator solids, miscellaneous contaminated non-organic and organic equipment) in containers (USA).

FIG. 2. Metallic scrap material embedded in cement (UK).

FIG. 3. Standard cylindrical drums used for packaging LILW (Argentina). Left: 200 L stainless steel drum; right: 400 L carbon steel drum with an epoxy paint inside and outside.

FIG. 4. Disposable large volume container for LILW from mild steel with removable lid and durable paint finish (UK).

containers must provide confinement during interim storage and transport. Examples of typical containers used in Member States for different types of LILW and HLW are shown in Figs 3–7.

The term ‘waste package’ as defined in Ref. [5] means a product of waste conditioning that includes the waste form and any containers and internal barriers (e.g. absorbing materials and liner) as prepared in accordance with requirements for handling, transport, storage and/or disposal.

2.2.2. Waste acceptance criteria

Waste acceptance criteria (WAC) are derived from assumptions of safety and performance assessments of the disposal facility. Establishment of WAC is the responsibility of the disposal facility operator in conjunction with the relevant national authorities/regulatory bodies. Verification of compliance of radioactive waste packages with WAC constitutes the primary method by which the operator of the waste disposal facility ensures the long term performance of the repository. To accomplish this task, the releases of radionuclides to the environment must be limited and controlled, and environmental and human health protection goals realized, by the proper design of the waste package and the disposal facility.

FIG. 5. 1500 L stainless steel container for cemented cladding hulls and end fittings (France).

FIG. 6. Shielded cast iron cask, typically used for transport and storage of high dose rate LILW (Germany).

There is a situation when waste packages are produced in the absence of a disposal facility and therefore no applicable WAC are available to guide the design and production of the packages. In this case the packages may be produced and fully characterized in accordance with the best engineering assumptions based on the experience and practice of other Member States. In such circumstances long term storage of these waste packages is a certain outcome, and it is inevitable that the storage facility will develop a set of acceptance criteria of their own for waste packages generated under these conditions.

In addition, transport regulations [7] place a set of overlapping criteria on the waste packages which will be transported from production to storage or from storage to disposal. These include surface dose rate, surface contamination limits, weight, size, total activity and structural integrity requirements. This means that the WAC constitute an agreement among the waste generator, transporter, and waste storage or disposal facility operator regarding the minimum characteristics of each waste package produced for storage and/or disposal. Meeting these criteria determines how the waste packages will perform under conditions of storage, transport, and ultimately emplacement in a disposal facility. In the past, WAC were thought to be of primary importance only in determining and ensuring the ultimate performance of the waste disposal system. Under conditions of long term storage awaiting disposal, the

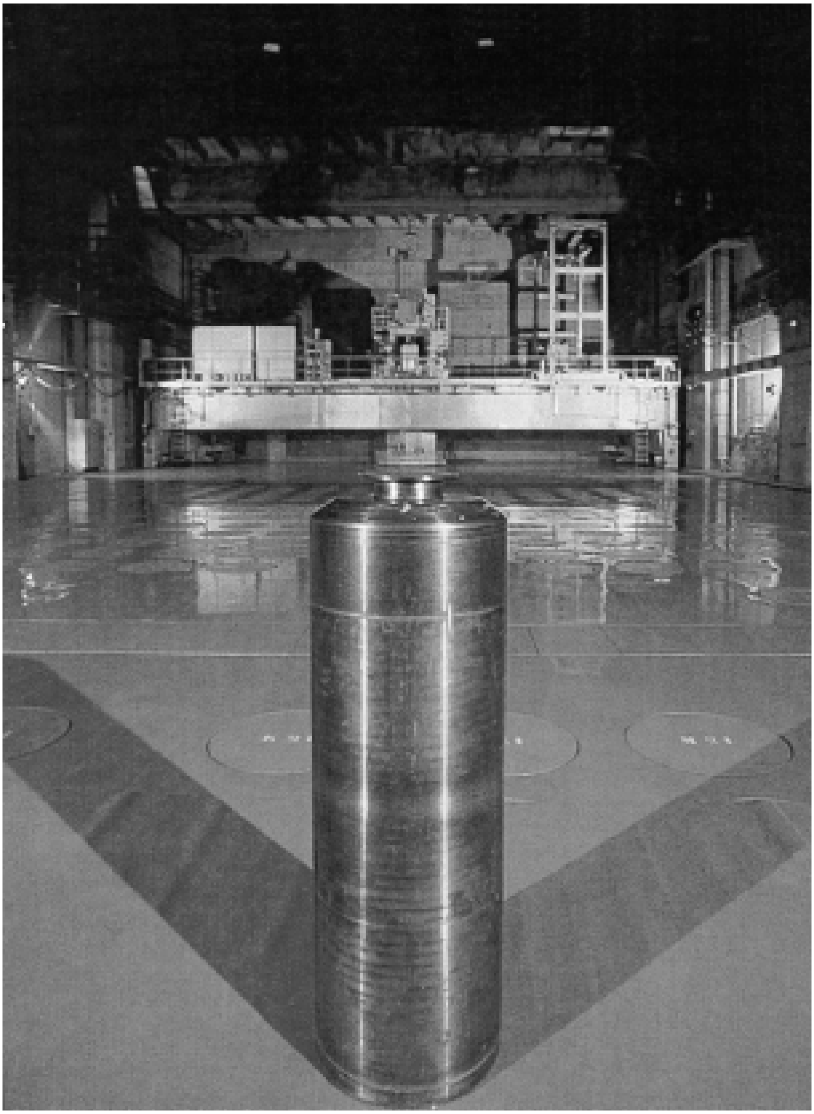

FIG. 7. 150 L stainless steel canister for vitrified HLW (France).

package must successfully maintain its characteristics under two very different environments. At either the interim or the long term storage facility, the facility operator can refuse to receive waste that does not comply with the requirements of WAC as directed by the operator's licence conditions.

Typical WAC address a wide range of physical, chemical and radiological criteria essential to the safe and effective performance of the waste package. Since some packages have a limited design life outside the disposal facility, the WAC have become very important in ensuring that, after storage, the waste package can still be safely moved. Since a waste package consists of a waste form and a container, a specific set of technical requirements can be addressed to them separately and to the waste package as a whole. For a waste form, these criteria concern but are not limited to the following, depending on the disposal site requirements:

- Waste composition
- Chemical durability
- Immobilization and/or stabilization
- Structural stability
- Respirable fraction
- Distribution of activity.

WAC for waste containers may cover the following parameters:

- Internal pressure
- Mechanical integrity
- Properties affecting primary confinement
- Venting
- Compatibility with the waste form.

Each waste package must meet a general set of criteria in addition to requirements specific to the waste form and waste container. WAC applied for waste packages generally include the following:

- Seal integrity
- Free liquids
- Gas generation
- Flammability
- Radionuclide inventory
- Fissile mass
- Decay heat
- Radiation dose rate and surface contamination
- Configuration and weight
- Identification.

Waste packages may be subject to additional constraints due to limitations or special conditions present at the storage facility that do not exist at the disposal site. For instance, floor loading and entrance dimensions may limit the package size and weight permitted for storage. When a disposal site is available and has WAC, the requirements must be compared and the most conservative set chosen for the waste packages.

2.2.3. Waste specifications

Waste package specifications are the set of detailed quantitative requirements to be satisfied by each package, indicating the procedure by which it may be determined whether the specified requirements are satisfied. Where the WAC for the disposal facility have not been defined, or waste packages must be fully characterized, it may be necessary to develop waste package specifications in place of the WAC. These specifications are considered as design output, and are intended to control the radiological, physical and chemical characteristics of the waste to be produced, processed or accepted from another organization. Waste specifications are usually oriented towards the performance of waste packages or control of operating facility processes and may be used as a contractual vehicle to control subcontracted conditioning operations. Waste specifications, like the WAC, should take into account intended storage/disposal facility parameters and transport regulations and should incorporate relevant parameters of the WAC, if they exist.

While WAC are generally facility or site specific and may embrace many different types of package, waste package specifications are specific to a particular type of package and are used to define the characteristics and attributes of a waste package.

2.3. REQUIREMENTS FOR STORAGE FACILITIES

2.3.1. Design requirements

The main functions of a storage facility for conditioned radioactive waste are to provide safe custody of the waste packages and to protect both operators and the general public from any radiological hazards associated with radioactive waste. The design of storage facilities will have to meet the national regulatory standards and basic safety principles, as described in Ref. [1]. The design proposed should follow these general principles and aim to reduce the probability of accidents to an “as low as practicable” level. In this context, the facility should be capable of maintaining the “as-received” integrity of the waste package until it is retrieved for disposal. The storage facility must protect the waste from environmental conditions, including extremes of humidity, heat and cold, or any other environmental condition which would degrade the waste form or container. Local climatic conditions may result in the need for cooling or dehumidifying the store atmosphere to avoid possible deterioration of the waste packages.

Storage requirements mandate external dose rate and contamination limits for waste packages to be accepted by the facility in order to protect personnel. A maximum allowable dose rate at the surface of each package should be defined for specific interim storage facilities or parts of facilities. In other respects the storage facility usually adheres to the waste acceptance requirements of the disposal facility. The storage facility should minimize radiation exposure to on-site personnel through appropriate siting and shielding.

The storage facility may be associated with an area for inspection (including sorting and/or non-destructive examination), certification and labelling of waste packages. The storage facility is usually divided into areas where low contact dose rate packages are stored, areas where packages not meeting WAC are stored, and a shielded area where high contact dose rate packages are kept secure. The design of the facility usually permits package stacking, sorting and visual inspection.

Provision for maintaining a database keeping chain-of-custody for each waste package in storage must be included in the design. Key information about the waste package should include the total radionuclide content, the waste matrix used for immobilization, the treatment and/or conditioning method (as applicable), and the unique package designator. A hard copy file should follow the waste package from conditioning to its final disposal.

Storage facilities should be designed to allow control of any contamination from gaseous or liquid releases. Adequate ventilation should be available to deal with any gas generation during normal operation or possible accident conditions. Provision for fire protection and for decontaminating individual containers and facility surfaces should also be made. Arrangements must be made to treat (or transport to a processing facility) potential accidental releases.

Storage facilities are often built in anticipation of a need, and have inherent limitations in the types and quantities of waste packages they might receive. Of necessity, storage facilities will provide space for non-immobilized waste (NIW) as well as immobilized and fully conditioned waste. Also, the initial design often needs to be changed in terms of space required, floor loadings and type of waste storage required. Because of these uncertainties, design criteria for storage facilities should take into account the following considerations:

(a) Adequate segregated storage should be provided for NIW and/or conditioned radioactive waste with anticipation of future storage needs if several types of package are stored in the same facility. These needs are, in turn, determined by the waste processing requirements and capabilities and the availability of specific treatment or disposal facilities, as well as package storage life and conditions. NIW should be stored in a form and manner that limit the risk of dispersion. NIW must be segregated according to its hazard level. Waste with short lived radionuclides that is to be held for decay must be segregated in a way that permits discharge as cleared waste when clearance levels are attained, as authorized by the regulatory authority.

(b) Emplacement, storage and retrieval of waste packages should be designed to keep exposure of personnel as low as reasonably achievable.

(c) The storage capacity of the facility must be designed to accept the maximum operational holdings anticipated from the system. The store should contain enough spare capacity to accept the contents of another storage unit whose integrity may be breached or suspect. Appropriate equipment for transfer between operational and spare units must be available.

(d) In the design of storage facilities for conditioned radioactive waste, consideration must also be given to:

- Waste package handling;
- Clear identification of stored waste packages and record keeping;
- Provision for inspection and monitoring of stored waste;
- Provision to prevent possible degradation of waste packages during storage;
- Provision for adequate environmental conditions (heating, cooling, humidity control) to ensure proper conservation of waste packages during their storage in the facility;
- Provision for cooling heat generating waste;
- Provision for fire protection where combustible waste is present;
- Provision for gas dissipation if gas generation is anticipated;
- Provision for criticality control where a considerable amount of fissile material is present in the waste;
- Provision for prevention of unauthorized access;
- Retrieval of the waste for further treatment, immobilization or disposal, or in the event of an accident which requires relocation of the waste;
- Maintenance.

If buildings are planned to be used for storage of radioactive waste they should be situated above the groundwater level, and certainly not in a flood plain. In cases where a subsurface storage facility is designed, this facility should be constructed with appropriate systems to protect against in-leakage of groundwater.

2.3.2. Operational requirements

The operations to be carried out in a storage facility will be limited to receipt, emplacement, integrity control (if required), retrieval, and preparation for dispatch of waste packages. The interim storage operations are essentially passive for the long period of time when waste packages are pending retrieval (most probably in bulk) until the repository facility is established. All operations concerned with storage must be carried out within the written authorized procedures.

2.3.2.1. Receipt and emplacement

The waste receipts should be programmed in advance. The store manager must examine the information to confirm that the waste package is acceptable for storage (e.g. correct packaging standard, radiation levels within limits). If the package is unacceptable, the details are to be recorded and the documents returned to the consignor with an explanation or a request for further information. Package acceptance qualification conditions should include, but not be limited to: maximum allowable weight per package; mechanical resistance for the stacking of packages; satisfactory corrosion resistance of the container material; sufficient resistance to a standard fire test; and no loss of integrity after a drop test from a height related to the package transport condition. The above tests are designed [7] to confirm the adequacy of the standard packaging design and should be performed occasionally during waste package production.

In the case of external contamination, the package must be decontaminated and rechecked before interim storage is authorized.

On acceptance, the equipment required for transport of the waste package to the store should be selected, and the store operator should proceed with this equipment and prepare the appropriate documentation to store the waste. The operator must be trained in the appropriate methods of radiological protection and in the use of radiation protective equipment if needed during handling of the waste package. At the store, a suitable location for the waste package should be identified and the location details recorded. The waste package would be placed in the chosen location. Segregation of waste types is desirable to facilitate a planned retrieval for further treatment or any unplanned retrieval that is revealed as necessary by periodic inspections for possible degradation of waste containers, and in case there are categories of waste to be placed eventually in particular repository locations.

The information provided by the consignor and the storage location of the package are incorporated in the central store records.

2.3.2.2. Integrity control

Adequate conditions for safe storage of waste packages should be maintained during the storage phase to avoid deterioration. Proper radiation protection measures must be applied to ensure that exposure to workers and the public is kept as low as reasonably achievable and that there is no contamination of the store or the waste packages. Monitoring should be undertaken to ensure that contamination has not occurred. The frequency of the monitoring will depend upon the quantity and type of the waste packages.

The records of the store inventory should be kept up to date, and the store contents periodically checked against the records.

2.3.2.3. Retrieval and dispatch

Following receipt of a request to retrieve a package from storage, the store manager should obtain the details of the particular waste package from the store's records and pass them to the appropriate party. If the details are in order the package may be accepted for removal from the storage facility. Once the store manager has authorized the release of the waste package, it is retrieved from the store and taken to the dispatch area. Here, the package should be monitored for radiation levels before it is released. The details of the waste package will be transferred to the transport records and the waste packaged for transport in accordance with the requirements of the transport regulations [7]. The package storage records should be amended to record the date of dispatch and the receiving party.

2.4. SAFETY ASSESSMENT OF STORAGE FACILITIES

A safety assessment must be carried out as part of the licensing process to demonstrate that the storage facility complies with regulatory requirements. The assessment will need to demonstrate that doses and risks remain within established criteria and meet the ALARA principle. Safety will need to be assessed for both normal operations and foreseeable accident conditions. The safety assessment must consider incidents arising both from internal process related events (e.g. internal fire, dropped waste packages, failure of containment of the waste packages) and from external hazards (aircraft crashes, transport accidents away from the facility, earthquakes, tornadoes and external fires).

The first stage of the assessment involves looking at radiological safety qualitatively to obtain a preliminary overview of the facility design concept. From this review, sensitive areas of design and/or operations may be identified, and any such areas can be subjected to a more rigorous quantitative safety assessment.

While the intermediate level waste (ILW) store will contain large inventories of radioactivity, the fact that the wastes have been immobilized in a stable matrix should result in a low accident risk. If the concentration of fissile material in the wastes is high (a concern of nuclear safety), the criticality risk will need to be assessed. The NIW store may contain smaller inventories of activity but the fact that those wastes are not immobilized in a stable matrix may result in a higher risk owing to a greater release fraction being available in the event of an accident.

The safety impact due to the receipt of an externally contaminated waste package should also be assessed. Possible causes of contamination are failure of a seal or sealing mechanism, overfilling of the container, or failure of the manual inspection procedure for contamination checking prior to emplacement into the store. Engineered and administrative controls incorporated to mitigate such an event should be addressed.

The safety assessment of a storage facility should consider degradation or failure of the waste package, which could occur for several reasons, including: corrosion of the container; gas generation in the waste matrix; decomposition of the waste package due to adverse change in the waste form; or an accident resulting in mechanical stress on the package in excess of its design capability. Other operational failures or accidents that may have to be considered in the safety assessment include but are not limited to ventilation failure, spills, fire, electrical failure and natural disaster. Assessments of possible accidents should correspond to the national objectives for safety analysis. Even if such failures or accidents should occur, the consequences would be of minor importance because the low mobility of the immobilized activity would result in minimal airborne or waterborne contamination.

The design of the facility should prevent water in-leakage to the store.

2.5. QUALITY ASSURANCE

In practice, quality assurance (QA) as applied to the storage of radioactive waste is divided into five principles of equal importance: general principles of QA in radioactive waste management, QA programme considerations, management, performance, and assessment.

Taking these general QA principles into account ensures that each step in the process (in this case, waste storage) (a) reflects health, safety and environmental concerns, (b) considers special needs or requirements of the national system, and (c) adequately anticipates the system’s requirements where uncertainties exist. It is also necessary to test the ability of the system to deal with storage issues created by waste generated outside the system.

Programme considerations require: formalization of the QA programme to ensure that storage facilities are designed, constructed and operated safely in accordance with specified requirements, and that they receive waste packages produced in the same way; that WAC for transport, interim storage and disposal are met; and that all regulations and conditions of the license are satisfied.

The QA management responsibility acknowledges that all work is a process that can be planned, performed, assessed and improved. Although the individual performing the work is responsible for quality, it is the function of QA management, by providing planning, organization, direction and control of the work, to remove barriers to success and promote a cycle of continuous improvement in products and processes.

QA performance for storage facilities includes such elements as design control and verification, peer review, data collection and software control, waste package specifications, and control of procured goods and services. QA for performance also assesses:

- Personnel performance and qualifications, and acceptance of items and services;
- Control of work processes, including the interfaces that exist between generation, processing, treatment, storage, recovery and disposal of waste;
- Storage, handling and shipping, including the assessment of all controls placed on the handling, dispatch, decontamination, storage, packaging and transport in order to prevent accidents, prevent container deterioration, and ensure the validity of analytical operations;
- Control of waste and operational status, including failed waste packages, identification and correction of substandard operational equipment and other items important to safety;
- Identification and control of items important to safety, including acceptance inspection and testing;
- Inspection hold points, surveillance and process monitoring;
- Identification of critical areas for inspection;
- Test control and control of measuring and test equipment.

Finally, QA assessment, as applied to the storage stage, includes activities by management for product verification, self-assessment and independent verification. However, QA applies to all elements of the waste management system, and can measure their interface and the system’s effectiveness. Years of experience have shown that any management system left to itself will deteriorate over time. QA assessment therefore becomes the most important part of the QA programme, because it provides for measurement of programme effectiveness before, during and after the storage stage of waste management, and for continuous improvement of the quality of the entire process.

3. PRODUCTION OF WASTE PACKAGES

3.1. CATEGORIES OF RADIOACTIVE WASTE

Radioactive waste is generated from the nuclear fuel cycle, medicine, industry and research activities. At least 95% of all radioactive waste generated is low and intermediate level waste. Other categories, such as high level waste including spent fuel declared as waste, are also produced, albeit at significantly lower volumes. Each waste category is described below.

3.1.1. Low and intermediate level waste

Radioactive waste in which the concentration or the quantity of radionuclides is above the clearance levels established by the national regulatory authority, but which has a radionuclide content and thermal power below those of high level waste (HLW), is addressed as low and intermediate level wastes (LILW) [8]. LILW is often separated into short lived and long lived waste. The term 'long lived' refers to radionuclides with half-lives usually greater than 30 years. As practised in several Member States, short lived LILW may be disposed of in near surface disposal facilities, whereas plans call for the disposal of long lived LILW in deep geological repositories.

The boundary between short lived and long lived wastes cannot be specified in a universal manner with respect to concentration levels for radioactive waste disposal, because the levels will depend on the actual radioactive waste management option and the properties of the individual radionuclides. However, in current practice with near surface disposal in various countries, the activity concentration is limited to 4000 Bq/g of long lived alpha emitters in individual radioactive waste packages, thus characterizing long lived waste which is planned to be disposed of in geological formations. This level has been determined on the basis of analyses for which members of the public are assumed to access inadvertently a near surface repository after an active institutional control period and perform typical construction activities (e.g. constructing a house or a road).

Applying the classification boundary, consideration should also be given to accumulation and distribution of long lived radionuclides within a near surface repository and to possible long term exposure pathways. Therefore, restrictions on activity concentrations for long lived radionuclides in individual waste packages may be complemented by restrictions on average activity levels or by simple operational techniques, such as selective emplacement of higher activity waste packages within the disposal facility. An average limit of about 400 Bq/g for long lived alpha emitters in waste packages has been adopted by some countries for near surface disposal facilities.

In applying the classification system, attention should also be given to inventories of long lived radionuclides in a repository that emit beta and gamma radiation. For radionuclides such as ^{129}I and ^{99}Tc, allowable quantities or average concentrations within a repository depend strongly on site specific conditions. For this reason, national authorities may establish limits for long lived beta and gamma emitting radionuclides based on the analyses of specific disposal facilities.

For LILW the design criteria for storage facilities will be based mainly on dose rate from the waste packages at the time of production and emplacement, rather than whether the waste is short or long lived, as this determines whether remote handling and/or shielding is a requirement for package handling and store construction. In Member States with low national waste inventories it is recognized that a single store for all LILW may be appropriate, in which case the store design should recognize the higher specification for long lived waste. In the United States of America there is no special definition for intermediate level waste, and this waste is classified as 'high activity low level waste'. The requirements for storage of this waste would therefore be based on its activity and surface dose rate. Depending on the dose rate, this waste may be 'contact handled' (<2 mSv/h) or 'remote handled' (>2 mSv/h).

The possible hazard represented by the waste can often be significantly reduced by administratively controlling the waste as part of storage or after disposal. Although the waste may contain high concentrations of short lived radionuclides, significant radioactive decay occurs during the period of institutional control. Concentrations of long lived isotopes that will not decay significantly during the period of institutional control are controlled to low levels consistent with the radiotoxicity of the radionuclides and requirements set out by the national authorities.

3.1.2. High level waste and spent fuel

High level waste (HLW), including spent fuel (SF) if declared as waste, is characterized by large concentrations of both short and long lived radionuclides, so that a high degree of isolation from the biosphere (e.g. geological disposal) is needed to ensure long term safety. It generates significant quantities of heat from radioactive decay, and normally continues to generate heat for several centuries.

An exact boundary level between LILW and HLW is difficult to quantify without precise planning data for many parameters such as the type of radionuclide, the decay period and the conditioning techniques. Typical activity levels are in the range 5×10^4 to 5×10^5 TBq/m^3, corresponding to a heat generation rate of about 2–20 kW/m^3 for decay periods of up to about ten years after discharge of spent fuel from a reactor [8]. From this range, the lower value of about 2 kW/m^3 is considered reasonable to distinguish HLW from other radioactive waste classes, based on the levels of decay heat emitted by HLW, such as those from reprocessing spent fuel.

The design criteria for storage facilities will be based mainly on dose rate from the packages as well as on decay heat, which has to be removed from the packages. Various external hazards should also be taken into account.

3.1.3. Spent sealed radiation sources

Sealed radiation sources usually fall into the category of LILW, and they are used for a variety of purposes, from instrument calibration and low power electricity generation to sterilization of medical tools and treatment of food for preservation. Their physical form may be a ceramic or a metal solid, or a salt solid of the radionuclide encased in stainless steel.

High dose rate (>1 mSv/h) sources are usually housed in shielded containers constructed of lead, steel or depleted uranium. High dose rate calibration of instruments is usually accomplished with a self-contained calibration. Other sources are used in medical applications as radiotherapy devices and contain ^{60}Co or ^{137}Cs as ceramic pellets in a shielded head. A mechanical ram moves the pellet in and out of the shielding when therapy is required.

Extremely high dose rate sources are shipped to users in shielded transport casks and returned in the same way after use.

As with other LILW, the design criteria for storage facilities for spent sealed radiation sources will be based mainly on their dose rate.

3.2. BRIEF OVERVIEW OF VOLUME REDUCTION PROCESSES

Once waste is produced it is important to reduce its volume so as to lower conditioning, transport, storage and disposal costs. However, the overall lifetime costs are of prime importance, and volume reduction must therefore be balanced against the complexity of the conditioning process. A large variety of volume reduction methods are in use in Member States, generally based on mechanical, physical, chemical, biological or thermal treatment. Selection of the most suitable method depends on the nature of the waste, the preliminary sorting and the storage/disposal criteria.

Volume reduction and treatment of low and intermediate liquid and solid wastes have been described in several IAEA publications [9, 10]. Not covered in those reports is the volume reduction of highly radioactive metallic waste, such as cladding hulls. However, implementation of a supercompaction technique for this waste is under way in France. A selection of the most common volume reduction processes for liquid and solid LILW is given below.

3.2.1. Thermal treatment processes

Thermal treatment processes include a wide range of oxidative and pyrolytic technologies which are extremely effective methods for volume reduction of combustible wastes. These processes provide a high reduction of mass (up to 10:1) and volume (up to 100:1) by chemically destroying the organic portion of the waste, which often constitutes the bulk of combustible solid waste. Thermal treatment also yields residues containing concentrated radionuclides which are often more compatible with subsequent management steps (e.g. conditioning, transport, storage, disposal) than the original waste form. Another advantage of these processes is their versatility in that they are able to accept and process a wide spectrum of dry solid wastes, organic liquid wastes, wet solid wastes and, to some extent, aqueous liquid wastes.

Incineration is the most common thermal treatment process and has been applied for over 40 years (e.g. the rotary kiln, controlled air and fluidized bed incinerators). Some other processes that do not employ open flame combustion but still achieve thermal oxidation of organic materials are wet air oxidation, molten salt combustion, molten glass combustion and vitrification. Numerous types and sizes of incineration systems are in use in many countries for processing a variety of radioactive wastes, from low level power plant wastes and institutional biological wastes to high activity fuel reprocessing facility wastes. The end product of incineration, the ash, may need additional treatment and conditioning, including compaction, immobilization, melting or emplacement in a high integrity container to meet storage requirements [9].

3.2.2. Compaction of solid waste

Compaction is a process in which solid materials are mechanically compressed to achieve smaller volumes. Compactors are usually categorized by the force they develop for compressing the waste. ‘Low force’ or ‘low pressure’ compactors operate at less than 10 MN compaction force. They are capable of compressing ‘compactable’ waste composed mainly of plastic, paper, rubber and cloth. The achieved waste volume reduction factors range between 2 and 5, depending on the characteristics of the waste material and its initial bulk density.

In high force compaction, also referred to as ‘supercompaction’ or ‘ultra compaction’, the waste is first placed in sacrificial containers and then compressed. The waste package acceptable for storage and disposal can be produced by emplacement of the ‘supercompacted’ wastes (or pellets) into another container, the ‘overpack’, with or without encapsulation in cement, depending on the physical form (see Fig. 8). The sacrificial containers and the overpacks are usually cylindrical drums, although rectangular containers have also been used. High force compactors operate at a compaction force of 10 MN or higher. Supercompaction can be used to reduce the volume

FIG. 8. View inside a steel container partly filled with supercompacted LILW pellets to be stored with or without grouting (Germany).

of virtually all dry active waste, including paper, plastic and cloth, which are generally described as compactable, as well as other, heavier waste materials such as metals, concrete rubble, glass, wood, motors, electrical and mechanical components, sand and other materials which are generally ‘non-compactable’ by low force compaction since these machines are unable to change the size or shape of such denser materials. High force compaction can compress waste materials to more than 90% of the theoretical densities. In the case of porous materials such as wood, the compressed density may exceed 100%. Depending on the nature of the waste material, the typical densities of supercompacted waste range from 1000 to 3500 kg/m^3.

3.2.3. Melting

During the melting process most volatile radioisotopes evaporate and escape from the molten mass. Other radioisotopes concentrate in the floating slag layer, which then solidifies on top of the melt ingot. The ingot contains less radioactivity than the original batch of scrap metal, so that a decontaminating effect has taken place. Several variations of the melting process (induction/electroslag/plasma/microwave melting) are available for different materials. While some processes have been designed to process metals exclusively, others are more or less dedicated to inorganic materials such as incinerator ash. The main advantages of melting are: substantial volume reduction; the possibility of recycling originally contaminated metallic waste; and no need for further immobilization [9]. The disadvantages are: the need for adequate gaseous effluent control and a secondary waste treatment system; generation of secondary wastes; and substantial energy consumption.

3.2.4. Evaporation of liquid waste

Evaporation is a proven method for the treatment of liquid radioactive waste, providing good volume reduction or concentration of liquid aqueous waste, high decontamination and good concentration. The technique is well developed and its advantages and disadvantages are well understood. Radioactive waste evaporators are generally kept simple in design to reduce maintenance problems at the expense of loss in thermal efficiency. Some wastes do, however, require more complex design, and scraped film evaporators have been used for intractable low level wastes. The evaporator produces a clean condensate that can be discharged to the environment and a concentrate that must be encapsulated in cement or other media for long term storage. The main disadvantages are high capital, energy and maintenance costs, but they give large volume reductions and excellent decontamination factors.

3.3. BRIEF OVERVIEW OF CONDITIONING PROCESSES

In the selection of immobilization and packaging processes, it is essential to take into account compatibility of the waste with the matrix and container materials, and compatibility of the container with the interim storage and/or disposal environment.

Many immobilization matrices have been used, e.g. cements, polymers, polymer modified cements, bitumen and glass. Matrices must be evaluated for a number of properties including physical, thermal and radiation stability and mechanical performance. While taking into account the actual immobilization process, consideration must also be given to the storage and transport of the waste packages produced.

TABLE I. CURRENTLY AVAILABLE IMMOBILIZATION TECHNOLOGIES FOR RADIOACTIVE WASTE

Waste type	Immobilization process
Short lived low and intermediate level	Cementation, bituminization, polymerization
Long lived low and intermediate level	Cementation, bituminization, vitrification
High level	Vitrification

Objectives should be: to produce an essentially monolithic product suitable for long term storage; to satisfy transport regulations; and not to foreclose options for final disposal.

Table I summarizes currently available immobilization technologies. Whether or not spent fuel declared as waste will require some sort of encapsulation/immobilization for disposal depends on the waste acceptance requirements not yet set up in Member States.

3.3.1. Cementation

A variety of LILW are suitable for incorporation into cement matrices. The cementation process is simple, flexible, reliable and cost effective. This was the first solidification method applied, and considerable experience exists for the process. There is a wide potential for using this process, and the cemented product has certain inherent properties, e.g. radiation resistance, compatibility with many types of environmental conditions, and good actinide retention. Special chemical resistant cements with different additives are now being used, e.g. resistant sulphate cement and slag cement. Cement can also be used for the immobilization of waste contaminated with transuranium elements [11]. Disadvantages are that the final product volume is increased and it is not very suitable for immobilization of organic waste and waste with high salt content. Cemented waste is usually accepted for storage, whereas its acceptability for disposal finally depends on its characteristics and compatibility with the properties of the intended disposal environment.

3.3.2. Bituminization

Bituminization is currently being applied for the immobilization of the waste resulting from treatment of low and intermediate level liquid effluents [12]. The process has been in use for more than 20 years. The bituminized product has a very

FIG. 9. Grouting of a container filled with LILW drums (UK).

low permeability and solubility in water and is compatible with most environmental conditions. Some restrictions must, however, be exercised with regard to the incorporation of strongly oxidizing components, e.g. nitrates, biodegradable materials and soluble salts. Furthermore, questions may be raised concerning the long term physicochemical and radiation stability of bitumen.

Bituminization is typically a process for the immobilization of very low heat generating wastes. Its use is restricted to materials with low alpha contamination ($\alpha < 40$ TBq/m^3 in liquid waste). During storage of bituminized waste, special care has to be taken owing to its flammability.

3.3.3. Polymerization

Polymers have been developed for immobilization of LILW that includes incorporation of evaporation concentrates, spent ion exchange resins, sludges and ashes [13]. Several types of polymer have been considered, including urea formaldehyde, polyethylene, styrene divinylbenzene (for evaporator concentrates), epoxy resins (for spent ion exchange resins), polyester, polyvinylchloride and polyurethane. The main disadvantage of the polymerization processes is that radioactive water can only be incorporated in small amounts. Polymers in most cases are compatible with organic wastes and are also efficacious for the incorporation of soluble salts, e.g. nitrates and sulphates. The use of polymers is severely limited by their ability to withstand radiation doses.

As with bituminized waste, the additional fire hazard must be taken into account when designing a storage facility for wastes incorporated in polymers.

3.3.4. Vitrification

At present the only process identified and applied for the immobilization of HLW is vitrification. Liquid wastes are converted into a solidified form by adding suitable glass forming materials and fusing these materials at a high temperature, typically greater than 1000°C. Some specific vitrification processes are described in Ref. [14].

3.4. EXAMPLES OF WASTE PACKAGES

Examples of waste packages are shown in Figs 9 and 10. Tables II, III and IV present an overview of relevant industrial and radiological characteristics for some typical LILW, HLW and spent fuel packages produced in Member States.

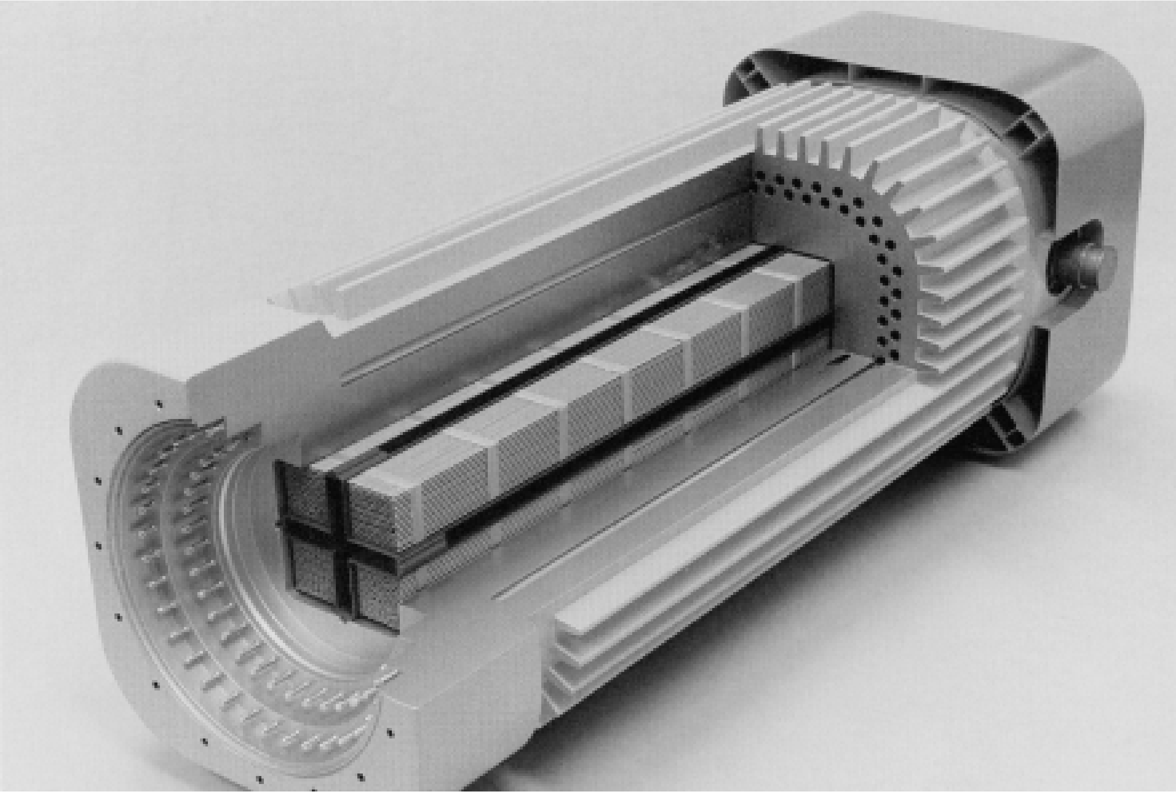

FIG. 10. Cutaway of a shielded CASTOR cask made from cast iron for transport and storage of spent fuel. Fuel rods, double lid system, drillings for neutron absorber and heat dissipation vanes can be seen (Germany).

4. STORAGE FACILITIES

4.1. GENERAL CATEGORIES

Waste storage which has been used or is currently in use falls into three general categories: subsurface storage, area storage and engineered storage.

Subsurface storage consists basically of emplacement of waste packages in engineered shallow trenches, frequently featuring a solid base of asphalt or concrete, with suitable backfilling material, in such a manner that retrieval is straightforward.

Area storage, also known as open vault storage, consists in emplacement of waste packages on the ground or on a constructed base, either in the open air or with a simple open sided covering.

Engineered storage refers to any fully contained building or structure specifically provided for the storage of waste packages. Engineered store designs are in many cases based on the need to handle large volumes of drummed or boxed waste packages with substantial surface dose rates. These stores may range from simply constructed enclosures to highly engineered facilities incorporating shielding structures and remote handling equipment, fully serviced with ventilation, effluent collection and instrumented controls. Typical examples of such storage facilities are listed in the Appendix.

4.2. STORAGE OF LOW CONTACT DOSE RATE LILW

LILW with low contact dose rates can usually be stored in any of the general facility categories described above.

4.2.1. Civil construction

4.2.1.1. Subsurface storage

Subsurface storage was commonly used in some Member States, notably the USA, to store large amounts of transuranic wastes for periods longer than 20 years. The cost of retrieval of these wastes today, coupled with the risk involved, has demonstrated that this option is not a prudent one, especially for developing countries.

Subsurface storage should only be considered where storage time is very short and climatic conditions favourable, such as in dry climates and locations remote from inhabited areas. In general, this type of storage is not recommended for future waste arisings unless appropriate environmental monitoring measures are taken.

TABLE II. TYPICAL LILW PACKAGES

Type	Country	Exernal dimensions (mm)	External height (mm)	Volume (L)	Container material[a]	Max. weight (kg)	Waste form
Drum	Austria	∅ 600	880	200	MSP	500	Concrete
NIROND 23 can	Belgium	∅ 305	365	28	Tin	50	Solid
NIROND 53 bottle	Belgium	∅ 310	600	30	PE	50	Liquid
NIROND 26 drum	Belgium	∅ 610	900	220	MSP	250	Solid
NIRAS/ONDRAF FS04 drum	Belgium	∅ 774	1073	400	MSG	1500	Bitumen
NIROND FC02 drum	Belgium	∅ 600	880	190	MSG	330	Bitumen
NIRAS/ONDRAF FI02 drum	Belgium	∅ 596	879	218	SS	262	Bitumen
		∅ 596	879	218	Cr plated steel	403	Concrete
COGEMA 220 drum	France	∅ 583.5	883	190	SS	300	Bitumen
Container	France	∅ 1000	1500	680	Asbestos/cement	2200	Concrete
CACZ 2/3 container	France	∅ 840	1200	392	Asbestos/cement	1800	Cement
CACZ 4 container	France	∅ 1000	1500	691	Asbestos/cement	3500	Cement

Drum	Germany	∅ 625	926	200	MS	650	Solid
VBA container	Germany	∅ 1060	1500	1300	Concrete	–	Solid
MOSAIK II container	Germany	∅ 1060	1500	1300	Cast iron	10 000	Various
Type IV container	Germany	3000 × 2000	1450	7400	Steel/concrete	20 000	Solid
Type V container	Germany	3200 × 2000	1700	10 900	MS	20 000	Solid
Type VI container	Germany	1600 × 2000	1700	5400	MS, concrete, cast iron	20 000	Various
High integrity container	India	∅ 1200	1500	1650	Concrete	20 000	Concrete
COVRA drum	Netherlands	∅ 596	880	200	SS	500	Concrete
Container	Sweden	1600 × 1200	800	1200	Steel	3000	Solid
Container	Sweden	1200 × 800	800	600	Steel	3000	Solid
Container	Sweden	1200 × 1200	1200	1600	Steel	5000	Solidified sludge of ion exchangers
Container	Sweden	1200 × 1200	1200	400	Concrete	5000	Solid
Container	Sweden	1200 × 1200	1200	850	Concrete	5000	Solid
Drum	UK	800	1200	500	SS	2000	Various, encapsulated in concrete
BNFL box	UK	1850 × 1850	1370	3000	MS, concrete lined	10 000	Individual items

TABLE II. (cont.)

Type	Country	Exernal dimensions (mm)	External height (mm)	Volume (L)	Container material[a]	Max. weight (kg)	Waste form
Container	UK	2438 × 6058	1320	18 000	MS	35 000	Various, grouted prior to delivery to disposal facility
Drum	UK	∅ 560	890	200	MS	100	Various, α contaminated
7A-217 type A box	USA	Variable	Variable	Variable	Wood	Variable	Solid
PPPL tritium waste drum	USA	∅ 565	86	200	MSP	450	Solids and water vapour on molecular sieves
Drum	Various countries	∅ 565	860	200	MSP	500	Concrete

[a] SS – stainless steel; MS – mild steel; MSG – mild steel galvanized; MSP – mild steel painted; PE – polyethylene.

FIG. 11. Area storage of waste drums.

TABLE III. TYPICAL HLW PACKAGES

Type	Country	External diameter (mm)	External height (mm)	Volume (L)	Container material[a]
Pamela 60 canister	Belgium	298.5 298.5	1200 1200	60 60	SS SS
Pamela 150 canister	Belgium	430	1346	150	SS
COGEMA 150 canister	France	430	1338	150	SS
COGEMA 1425 drum	France	1130	1707	1300	SS
COGEMA CBFC2 container	France	1000	1500	676	Reinforced concrete
BNFL canister	UK	420	1300	150	SS

[a] SS – stainless steel.

4.2.1.2. Area storage

Area storage may be considered for various waste packages such as mild steel drums with plastic liners containing pre-packed waste, ISO freight containers holding drums or pre-packaged items, and plastic drums. An example of area storage is given in Fig. 11. Routine inspection of waste packages is in many cases a feature of such stores.

Essential requirements for area storage would be absence of vegetation and delineation of the storage area by appropriate fences to preclude unauthorized access. Potential exposure to the waste packages and the lack of climate control make this method of storage inadequate for mild steel containers or drums.

4.2.1.3. Engineered storage

An engineered storage facility for LILW with low contact dose rates may be of simple construction, for example an inflatable building on an asphalt base pad. Alternatively a warehouse type construction with no arrangements for package handling, heating or ventilation is widely used.

Max. weight (kg)	Max. initial activity (GBq)	Max. initial dose rate (Sv/h)	Heat production (W)	Waste form
250	5.6E5 (β)	140	70	Glass
510	3.3E5 (β)	7.5	40	Glass/lead
500	1.8E5 (β)	12	20	Glass
500	6.6E6 (^{137}Cs) 4.6E6 (^{90}Sr)	1.4E4	4000	Glass
4500	6.3E4 (^{137}Cs) 5.2E4 (^{90}Sr)	–	115	Cemented cladding hulls
4000	3.15E3 (β/γ) 0.63 (α)	–	–	Concrete/ lead
550	4.5E7	4500	2500	Glass

Recently, more sophisticated engineered stores with full engineered features have been constructed. The facilities may include arrangements for package handling, shielding with concrete (or equivalent), remote inspection, ventilation, temperature control, effluent collection, and prepared building surfaces to aid decontamination.

4.2.2. Package handling

Waste packages may be handled in the following ways:

(a) Manually (for small packages with very low surface dose rate);
(b) With a lift truck (fork type for containers on pallets or clamp type for drums (Fig. 12));
(c) With a locally controlled overhead crane (with package hooks for containers or clamps for steel drums);
(d) With a remote controlled crane, sometimes computer assisted, with a telescopic arm and monitored emplacement devices. Such cranes are used by Belgoprocess in Belgium for LILW (Fig. 13).

TABLE IV. TYPICAL SPENT FUEL PACKAGES

Type	Country	External diameter (mm)	External height (mm)	Volume (L)	Container material[a]
CASTOR IIa	Germany	2050	6050	4080	DCI
CASTOR V/19	Germany	2440	5680	7150	DCI

[a] DCI – ductile cast iron.

4.2.3. Emplacement

Waste packages may be stacked or placed on shelves or in racks (Figs 14 and 15). Shelf arrangements are usually suitable for storage of liquid waste in approved small bottles. Free stacking is the most commonly used arrangement for containers and drums. Vertical stacking is usually limited by the load bearing capacities of the bottom-most containers as well as by drop height or seismic requirements. Alternatively, cylindrical packages may be stacked on their sides or grouped on stacked pallets.

4.2.4. Record keeping

On-line registration of waste package location and identity is not normally practised for LILW packages with low contact dose rates unless a nuclear criticality control is required. Manual bookkeeping or entry into a computer database is generally used.

4.3. STORAGE OF HIGH CONTACT DOSE RATE LILW

4.3.1. Civil construction

4.3.1.1. Subsurface storage

Subsurface storage facilities do exist (e.g. in caissons) but are not recommended for new arisings of LILW with high dose rates owing to difficulties of inspection and retrieval. An example of a storage facility for hulls and reactor components in India is shown in Fig. 16.

Max. weight (kg)	Max. initial activity (GBq)	Max. initial dose rate (Sv/h)	Heat production (W)	Waste form
112 000	4.07E8	1.3E–3 (γ + n)	42 000	LWR spent fuel
123 000	5.3E8	1.3E–3 (γ + n)	39 000	LWR spent fuel

FIG. 12. Handling a 200 L drum with a lift truck (USA).

FIG. 13. Interim storage of LILW packages (Belgium).

FIG. 14. Emplacement of a 200 L drum in the rack (Belgium).

FIG. 15. Emplacement of drums in racks for stacking (Belgium).

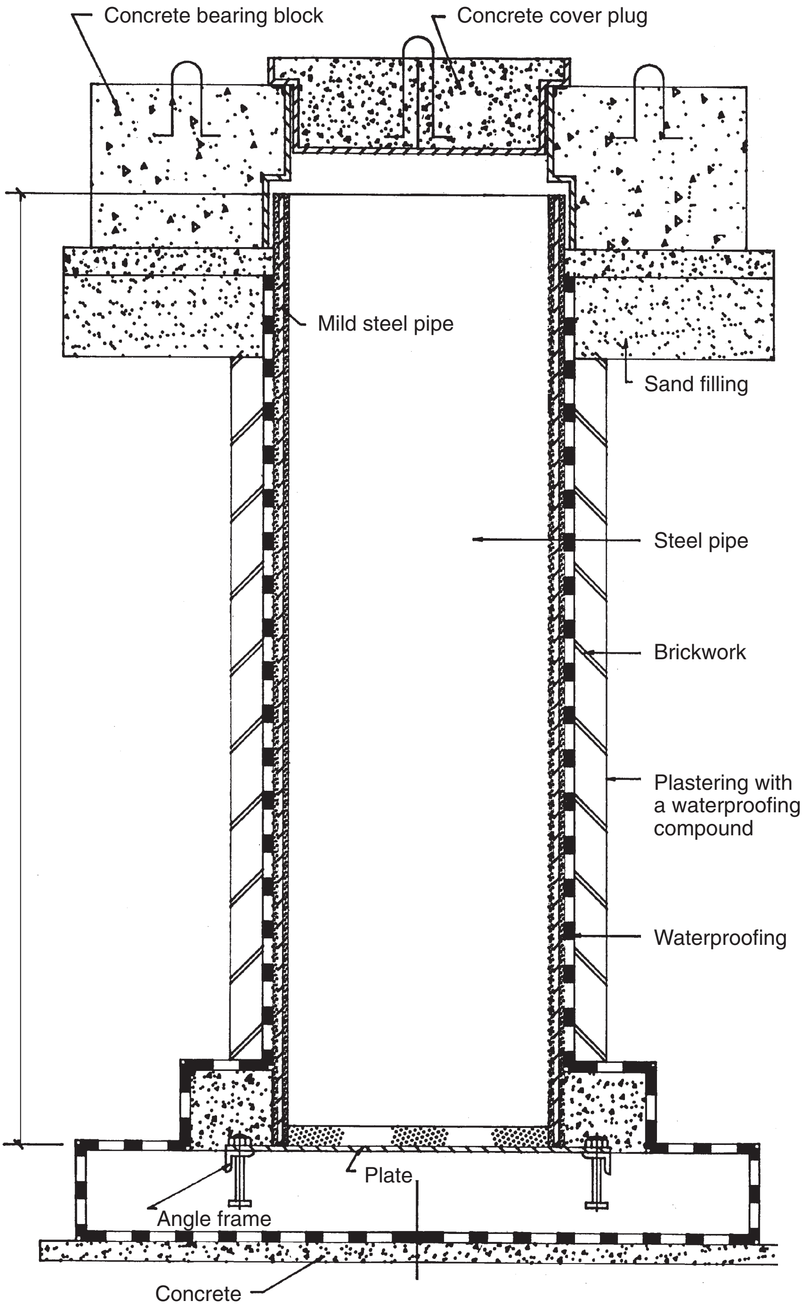

FIG. 16. Subsurface storage facility for hulls and reactor components (India).

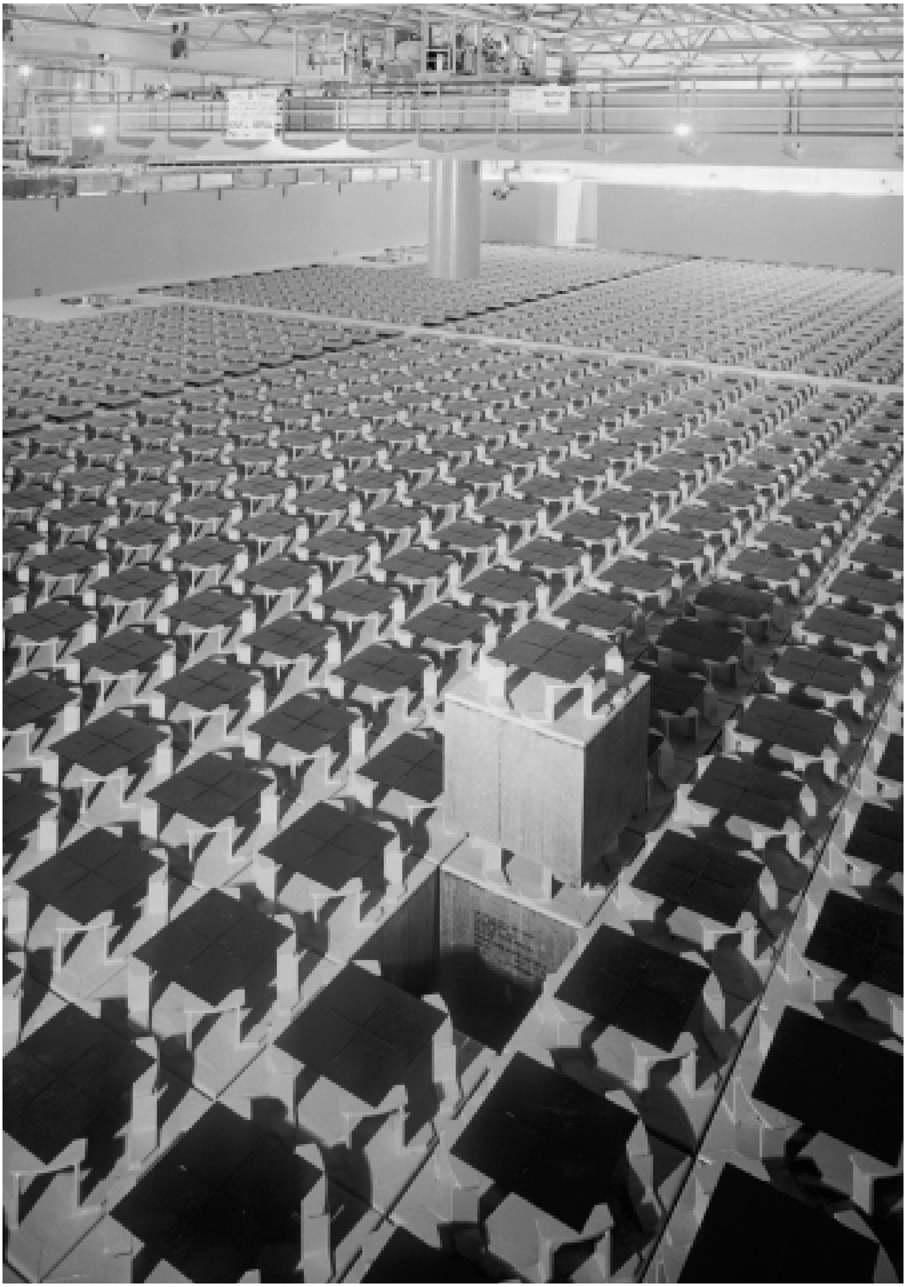

FIG. 17. Modern high contact dose rate LILW facility (UK).

4.3.1.2. Area storage

Area storage is suitable for waste packages placed inside approved individual shielded storage containers made from corrosion resistant materials. Area storage may also be provided for waste placed in corrosion resistant containers in an open vault structure with a solid base but, in addition, shielding walls (earthen or concrete) up to the stack level are used to limit dose rates outside the store. Owing to their high dose rate, packages are often stored in high integrity containers that are suitable for both area storage and transport.

4.3.1.3. Engineered storage

Engineered storage is the most commonly adopted practice for LILW with high surface dose rates, particularly where large numbers of packages are produced. The minimum standard of construction for these stores is a warehouse type building, fully contained, with a solid floor, adequate safety provisions for package inspection and sufficient shielding.

New facilities would be expected to be of a higher standard, incorporating equipment for package handling, a shielding provision inside the building civil structure, design arrangements to prevent water in-leakage, ventilation, and temperature control. An example of a modern storage facility is shown in Fig. 17.

An example of a small storage facility for vitrified long lived, high contact dose rate LILW is shown in Fig. 18. The waste arises from the decommissioning of a nuclear power plant (NPP) with a demonstration heavy water gas cooled reactor. The storage facility, together with a vitrification plant, is located in the NPP building.

4.3.2. Package handling

Package handling may be undertaken with:

(a) A shielded lift truck and/or gantry cranes for drums or containers;
(b) A remote controlled crane, using a remote controlled or automatic grab to emplace the packages in stacks inside the storage vault;
(c) A remote controlled trolley on which boxed wastes are stacked prior to emplacement (Fig. 19).

4.3.3. Emplacement

Packages may be stacked inside a supporting structure or in self-supporting arrays where stability under potential seismic loadings is demonstrated in the design. Pre-stacked packages on remote controlled trolleys are emplaced directly inside the

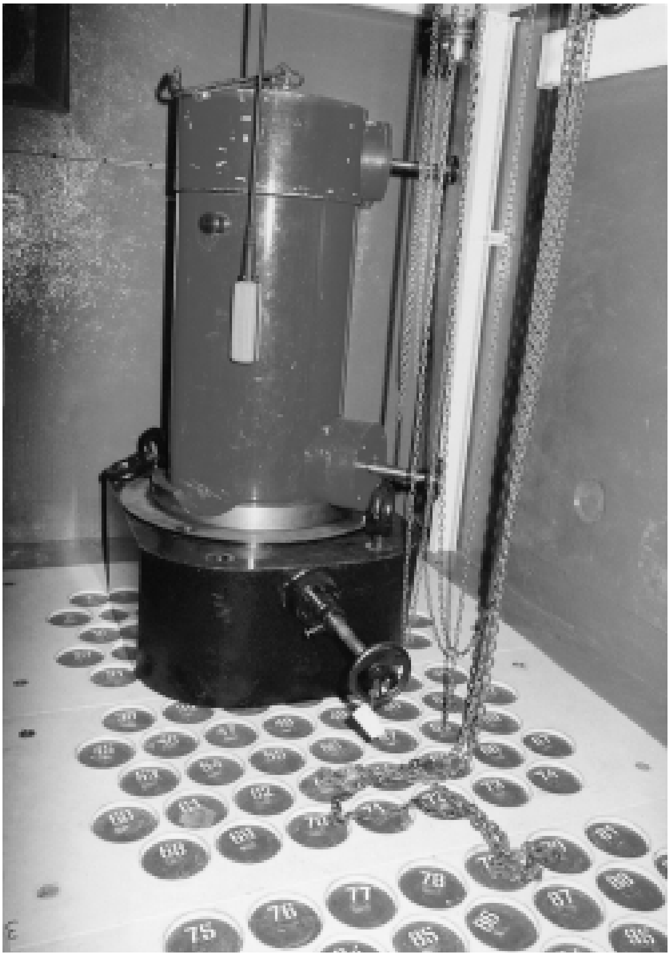

FIG. 18. *Small storage facility for vitrified LILW (Slovakia).*

vault (Fig. 20). Cylindrical packages may be stacked on their sides inside supporting structures (Fig. 21).

Transport casks also approved for storage may be emplaced directly inside the store, and are not usually stacked.

4.3.4. Record keeping

While manually recorded information is acceptable, most modern LILW stores for packages with high contact dose rates include arrangements for on-line registration of the package identity and storage location.

FIG. 19. Stacked packages on a remote controlled trolley awaiting emplacement in the waste store (UK).

FIG. 20. Pre-stacked packages inside the storage vault (UK).

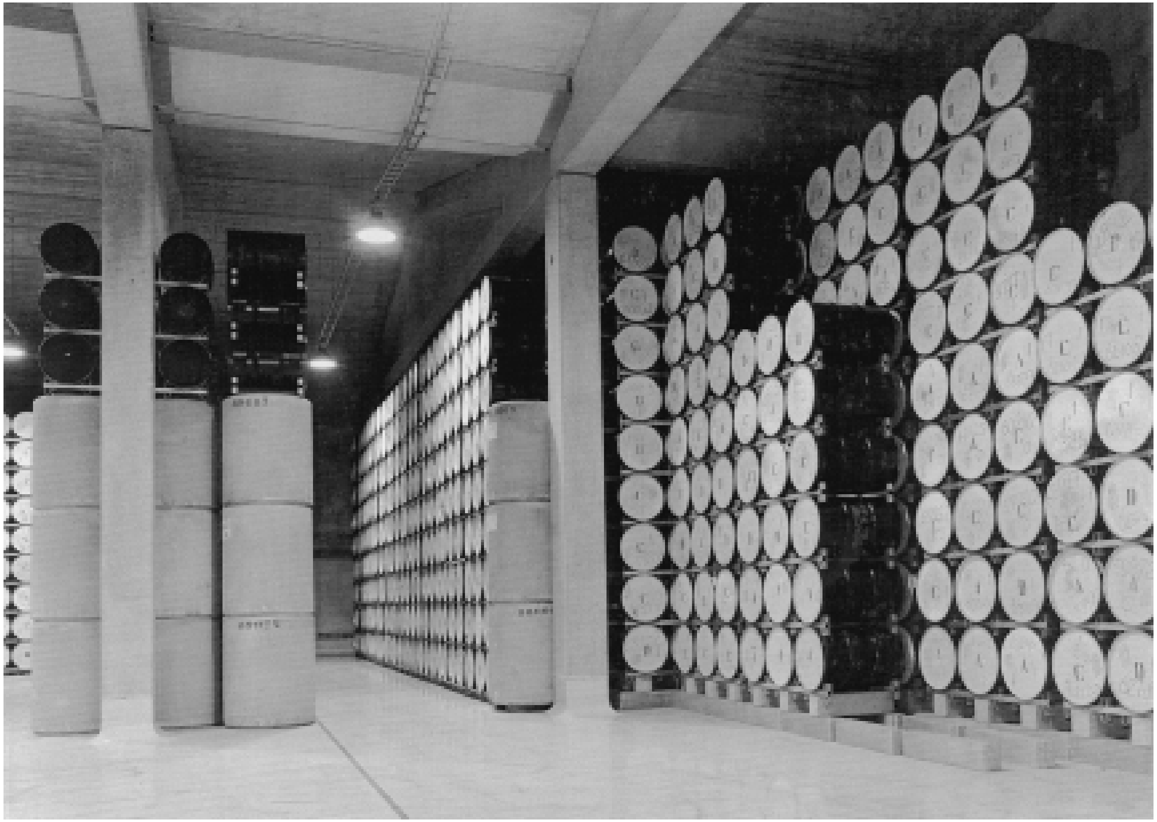

FIG. 21. Horizontal stacking of metallic waste drums (Netherlands).

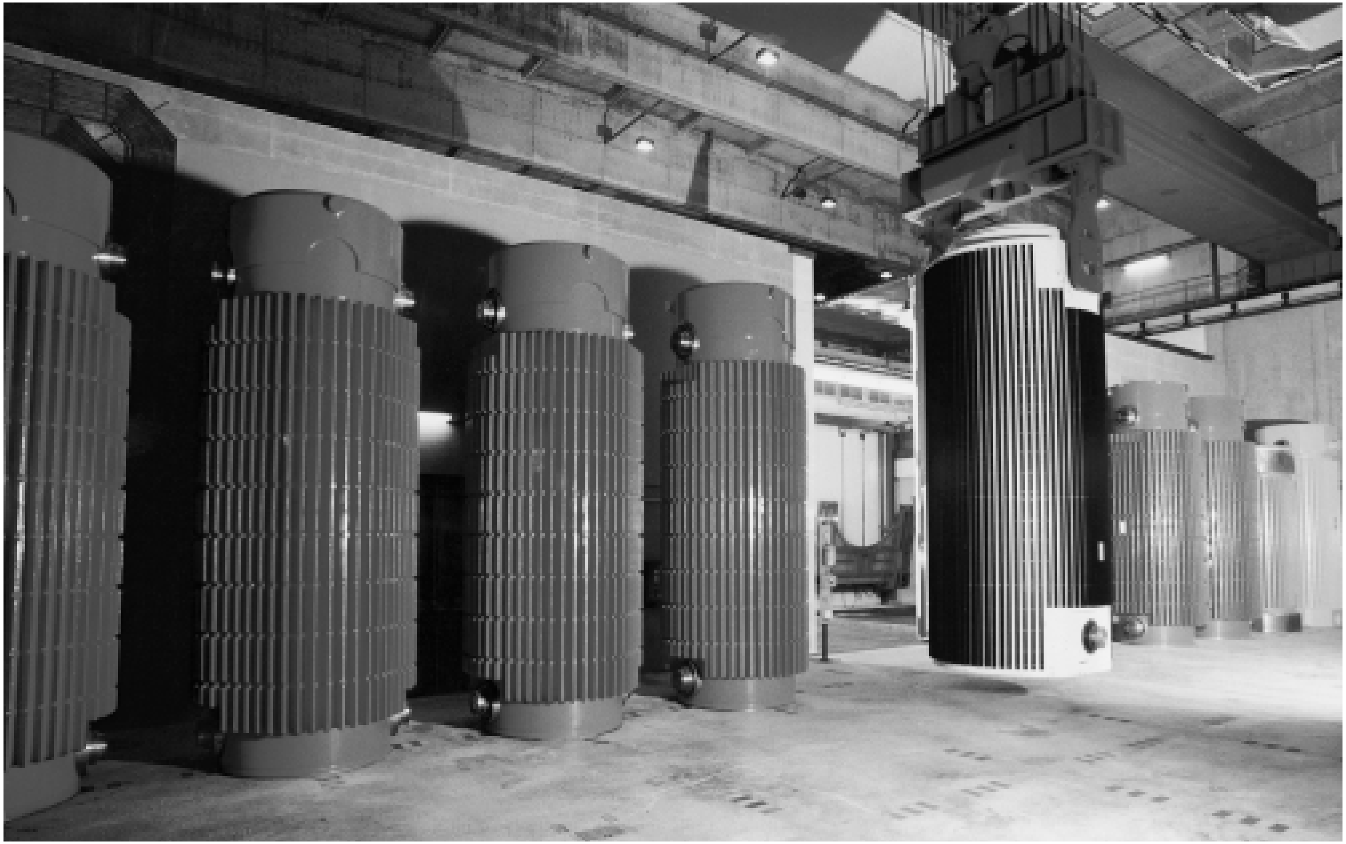

FIG. 22. *Storage of spent fuel transport casks (Germany).*

4.4. STORAGE OF VITRIFIED HLW AND SPENT FUEL

In some countries spent fuel is considered as waste. The comments below do not apply to spent fuel stored while awaiting reprocessing, which is the subject of separate reports.

4.4.1. Civil construction

4.4.1.1. Subsurface storage

Non-engineered subsurface storage is not acceptable for vitrified HLW and spent fuel.

4.4.1.2. Area storage

Area storage is only acceptable for vitrified HLW and spent fuel if the waste is contained in an accident-proof, self-cooling cask, providing appropriate shielding and guaranteed containment. Typically, the casks should be of the same standard as the approved containers used for waste transport.

4.4.1.3. Engineered storage

Engineered storage is normally required for vitrified HLW and spent fuel. In its simplest form this can involve storage of transport casks approved for storage within engineered structures which include additional shielding provisions and are designed to remove heat convecting naturally from the cask. An example of this is the storage of spent fuel awaiting direct disposal in Germany (Fig. 22).

High level waste canisters are commonly stored in pits or channels within a concrete vault. Cooling is achieved by natural convection or by forced ventilation. This is required in order to control the maximum temperature in the glass below the limit set by the waste package requirements. Such vaults may be constructed below ground level to assist radiation shielding. An example of such a facility in India is shown in Fig. 23.

The engineered stores for vitrified HLW are fully equipped with remote devices for package handling and sufficient shielding provisions inside the building structure that may lead to about 1.7 m or more of concrete (or equivalent). Stores are usually designed on a modular basis to allow extension when required. An alternative method of waste cooling may be provided by wet storage in water filled pools, with heat exchange facilities to remove heat from the circulating cooling water. At present, this technique is only used in the CLAB storage facility for spent fuel in Sweden (Fig. 24).

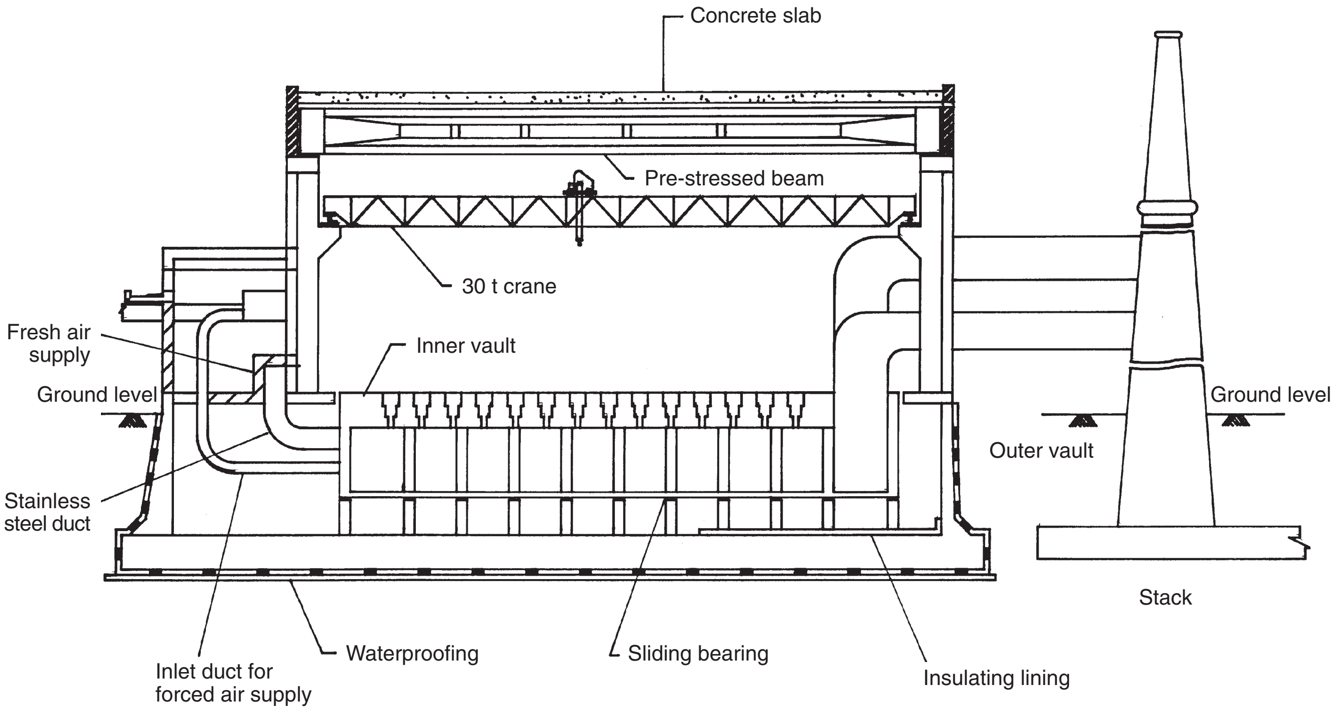

FIG. 23. Air-cooled storage facility for HLW (India).

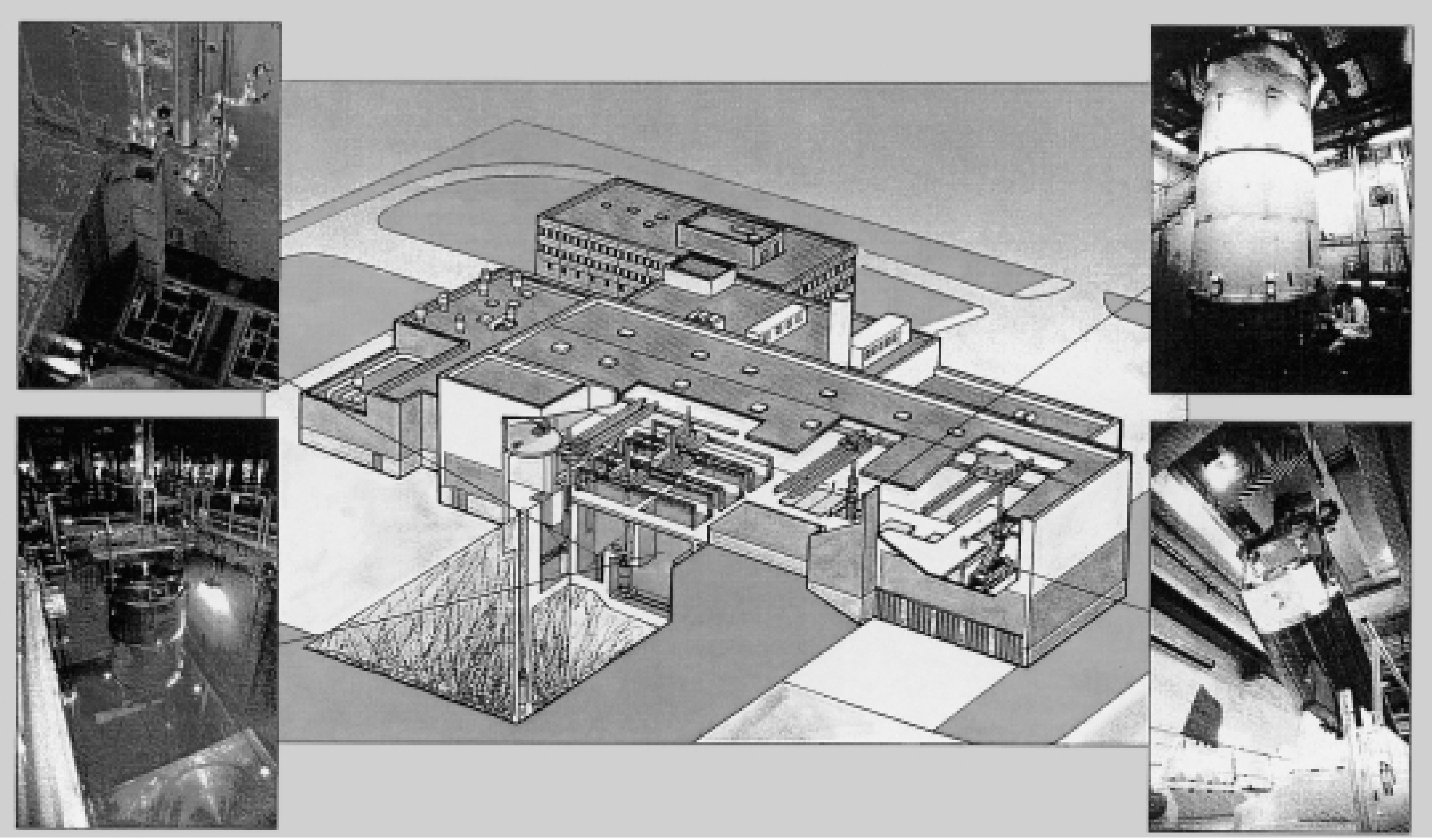

FIG. 24. CLAB storage facility (Sweden).

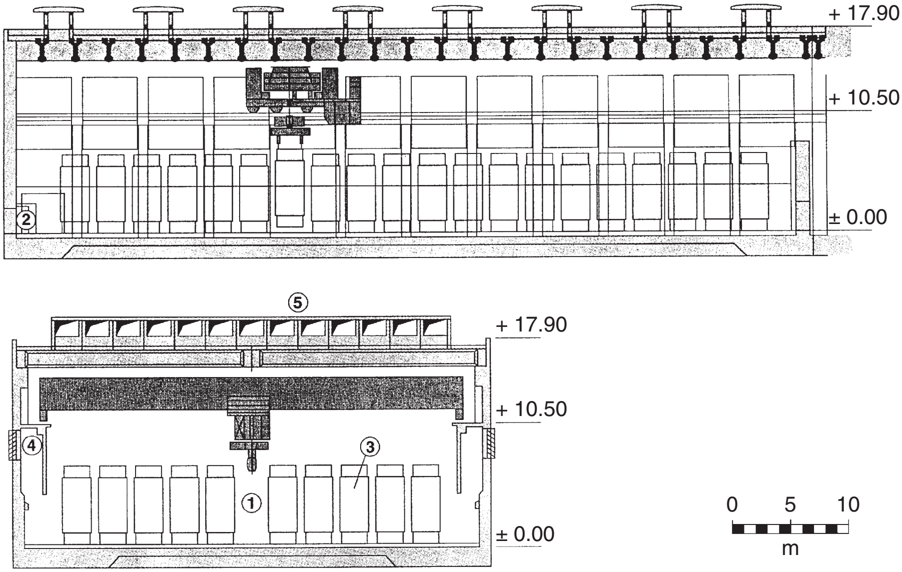

FIG. 25. Package handling of casked vitrified HLW using overhead crane (Germany). (1) container area; (2) airlock; (3) transport and storage container; (4) air inlet; (5) air outlet.

FIG. 26. Charging machine on top of the interim storage cell for vitrified HLW canisters (France).

4.4.2. Package handling

The casked vitrified HLW is normally handled by an overhead crane (Fig. 25). For the uncasked canisters with vitrified HLW, a remote controlled crane using a shielded grab (charging machine) emplaces the canisters into vertical stainless steel storage channels fitted through a concrete store face (Fig. 26). Concrete plugs are used to shield the radiation from the canister while loading or on completion of loading. Moveable shielding gates can be used to minimize radiation exposure during the loading operations.

4.4.3. Emplacement

Vitrified waste canisters are emplaced inside the stainless steel channels, usually in stacks up to 12 canisters high. A typical emplacement procedure is shown in Fig. 27.

4.4.4. Record keeping

Record keeping arrangements are as described in Section 4.3.4 for LILW with high contact dose rates.

4.5. STORAGE OF SPENT SEALED RADIATION SOURCES

Spent radiation sources from industry or from medical applications such as ^{60}Co, ^{137}Cs and ^{226}Ra are stored for decay (short lived radionuclides) or for conditioning (long lived radionuclides). These sources can usually be stored in LILW storage facilities, either in area storage or, preferably, in engineered storage facilities similar to those described in Section 4.3. Package handling and emplacement are as described in Section 4.3.

5. OPERATIONAL EXPERIENCE AND OPTIMAL STORAGE PRACTICES

Member States have acquired a significant amount of experience in constructing and operating all types of waste storage facility. Some States are in the process of retrieval of waste from substandard storage conditions, e.g. temporary subsurface storage in trenches, and there have been many individual examples of failures of

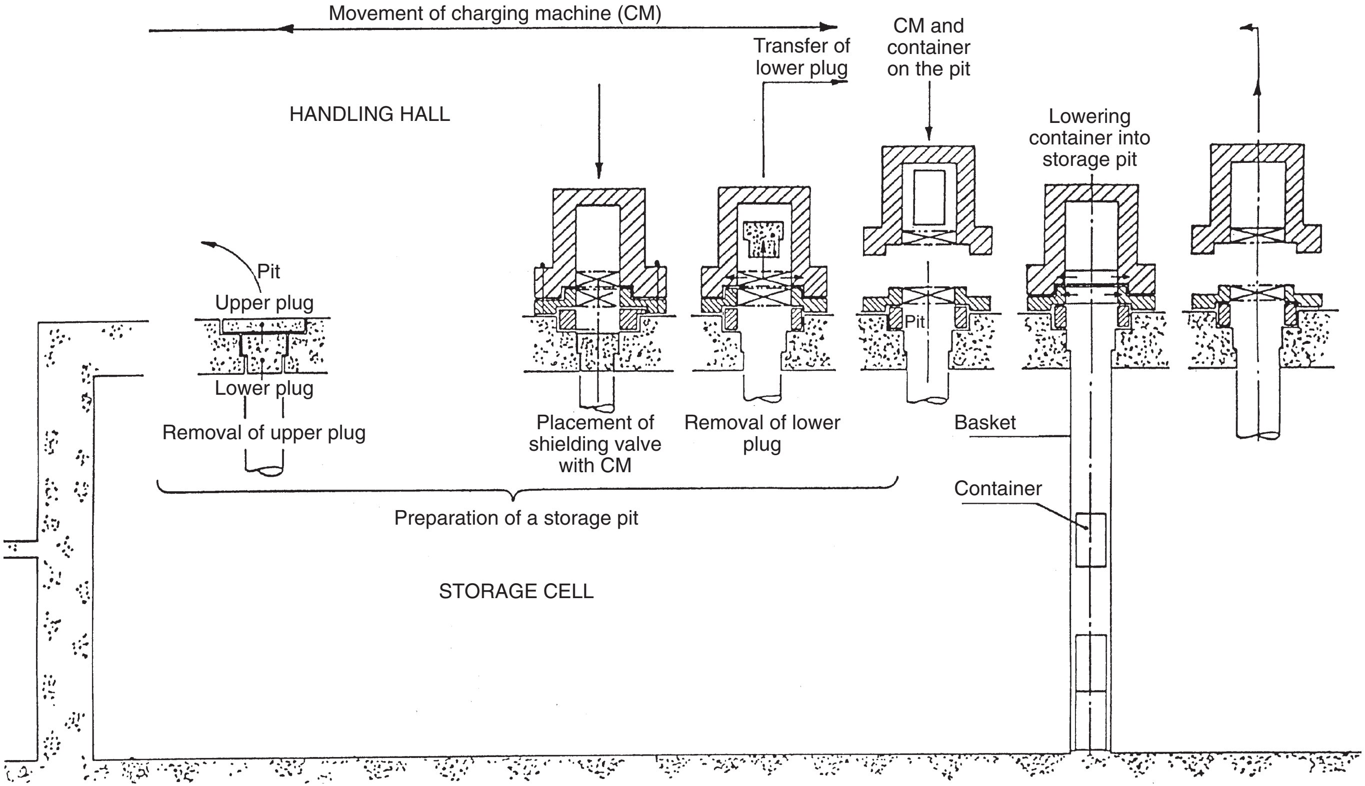

FIG. 27. Transfer of vitrified HLW canisters to storage pit (Belgium).

FIG. 28. Examples of corrosive failures of waste packages.

waste packages. Failures may be caused, for example, by chemical reaction generating explosive atmospheres within the packages, internal and external corrosion of the container, and galvanic reaction between stacked containers in a store. Figure 28 shows examples of corrosive failures.

The experience acquired by Member States demonstrates the importance and collective significance of their knowledge of the behaviour of waste packages during storage. Recognition that deficiencies may exist in current and past storage arrangements is expected to lead to the selection of optimal storage practices that can be recommended for use by Member States. However, operation of well designed and well constructed storage facilities for suitable waste packages has demonstrated that very few problems exist with stored waste packages.

5.1. OPERATIONAL CONTROL OF STORAGE CONDITIONS

To verify the predicted performance of a storage facility, on the basis of the safety assessment and design criteria, a number of operational control measures must be applied. They may be applied systematically or randomly, or they may involve continuous monitoring. Control measures may be accomplished locally for contact handled waste, or may be remote (e.g. cameras) in areas where personnel are not permitted routine access.

Observations and measurements are necessary to ensure that the storage structure remains in compliance with the original design specifications. In the case of subsurface or area storage without an engineered foundation, stability of the graded surface round the site must be controlled. Provisions for water run-off must be made to prevent degradation of the area surface. In the case of an engineered structure with an engineered foundation, regular inspections must be carried out to see whether degradation or deformation of the structure (foundation, walls, roof) have occurred.

Section 2 of this report listed the most important parameters to be controlled by the design of a storage facility. However, those of particular concern for operations are (a) air temperature and humidity, and (b) water in-leakage by collection in pits or sumps.

The collected liquid should be analysed for the following chemical and radiochemical parameters (as a minimum) to determine whether the liquid has arisen because of package failure or in-leakage of rainwater:

- pH,
- alpha activity (by counting and spectrometry),
- beta/gamma activity (by counting and spectrometry).

Corrective action would normally be necessary to seal leak paths or isolate failed packages should these occur. Some additional parameters should also be checked where appropriate:

- Air flow rate (air changes),
- Control of negative pressure inside the facility (when applicable),
- Outlet air control (filtration, sampling),
- Presence of particulates, organics and radionuclides in the exhaust air.

Site specific measurements should reflect a graded approach that depends upon the type of storage facility and the waste emplaced therein. For area storage (non-engineered), waste containers must provide complete confinement of the waste form and complete protection from environmental conditions which could damage or alter the waste form. Environmental monitoring would be limited to air monitoring by means of a permanent grid where routine samples are taken on a regular basis. Routine samples to monitor radioactivity in groundwater and surface water should also be taken and analysed to ensure that the waste packages in storage are not causing contamination of the ground and surface water.

The engineered storage structure is designed to contain waste packages. Contamination inside a storage facility under normal operating conditions is not usually expected. If an accident occurs that results in a loss of containment of the waste package, provisions for decontamination of the affected area of the storage facility should be available. This applies to both remote handled and contact handled wastes.

Radiological control should be performed in order to protect operators in both area and engineered storage facilities. In the case of an open air storage facility, the surface dose rate and surface contamination should be measured on packages. For packages of greater activity the dose rate should be measured remotely in a way that keeps the exposure of the personnel as low as reasonably achievable. In engineered storage, the same objectives are appropriate, although contamination may be monitored by air sampling or representative measurement of waste packages.

In a storage building, a contact dose rate should be verified adjacent to the outer wall. The external dose rates outside the storage building should be regularly monitored to ensure that they conform to the national standard for unrestricted access to facilities within a radiologically controlled area.

In cases when storage radiological conditions change (e.g. if stored packages are more radioactive than previously expected), shielding may be added to the interior main walls or to the waste package array.

Nuclear criticality control by fission neutron monitoring must be applied where fissile material in high concentrations (e.g. spent fuel, plutonium bearing wastes) is stored.

5.2. SURVEILLANCE OF WASTE PACKAGES

A number of key surveillance principles that apply to the storage of waste packages must be in place, whether the waste is stored at the point of generation or transported to a facility specially designated for that purpose.

5.2.1. Certification

Each package has a unique number and label, linked to a detailed manifest that represents its complete history. The records characterizing the waste should be maintained to demonstrate the total radionuclide content, chemical composition, type of treatment and conditioning, point of origin and contact organization in case of questions or problems, and to ensure that a real time inventory total exists.

5.2.2. Control of inventory location

Waste packages in storage are normally segregated so that only one type of package is present if the quantities of generated waste are large enough to make segregation easy and economical. The principle of segregation involves consolidating waste packages by type to facilitate surveillance and detection, and solution, if possible, of potential problems. Thus, where possible, alpha bearing LILW is segregated from beta/gamma LILW; short lived LILW is segregated from long lived LILW, etc. Non-conforming waste may be held for storage as long as it can be properly segregated. The storage facility may receive NIW, but this should never include uncharacterized waste. If the contents of the waste package are unknown, then proper segregation cannot be accomplished.

Waste packages received for storage may have unique characteristics associated with them, including size, design package life. The location of each package in the store should be recorded to facilitate inspection and retrieval (see Section 6).

5.2.3. Inspection

Although past practices have not always permitted the periodic surveillance of waste packages in storage, inspection and monitoring of the storage facility and its contents are now required unless the waste packages are subject to a comprehensive quality assurance system from the time of generation. When the storage facility has been designed to comply with rigorous requirements and safety assessments and the packages are produced in well qualified processes that have led to the establishment of specifications (which have been verified), then control of packages may not be required. Such packages may be exempt from surveillance requirements during storage. These considerations apply without difficulties to vitrified HLW and immobilized LILW.

Experience at numerous nuclear facilities has shown that a number of inspections may be required during interim storage. This is especially true when interim storage has evolved into prolonged storage where repositories have not become available in the time frame originally anticipated. Attributes that should be monitored include the adequacy of identification and the physical condition of the container. Such inspections may be performed remotely using optical aids (cameras, telescopes, etc.) in order to minimize personnel exposure. The adequacy of such remote inspection techniques should be demonstrated, particularly if they are relied on as the sole means of detecting container degradation. Inspection techniques should also include visual inspection when it is possible. For waste packed in a metal container, a visual inspection will demonstrate possible corrosion. For waste packed in a concrete container, stains and spills on the concrete may indicate diffusion of waste content through the container. Visual inspection also serves as an indicator for problems with packages to be further revealed by technical means. Where high activity wastes are involved, required inspections may be performed remotely by camera, together with air and liquid effluent monitoring.

Other attributes of importance to be monitored include the operability of cooling equipment where heat generating wastes are stored, as well as the operability of monitoring instrumentation.

The temperature of the waste package should be periodically monitored where thermal power of waste forms is sufficient to initiate accidents if active cooling systems fail in the absence of possible natural cooling. Also, where liquids are utilized for either cooling or shielding, periodic inspection of liquid levels should be performed. The frequency of such inspections should be derived from storage facility safety analyses but may require modification (increase in frequency) as facilities age or as dictated by operational experience.

Mechanisms should be established to ensure that corrective action is taken for any deterioration of packages, package identification or cooling/monitoring systems identified during inspections.

The detection of general package degradation may be feasible by means of sample inspection. Consequently, such packages containing the same matrix may be randomly selected for testing their integrity. Obviously, it is necessary to check any change in surface dose rate of the package in order to know the geometric distributions of activity. If abnormal increases in dose rate are detected locally, this means the partitioning of activity is no longer homogeneous and, in that case, repackaging is probably necessary. During this process and all inspection activities, operators should be protected from excessive exposure to waste packages, in particular when potentially failed packages are involved.

5.3. EXAMPLES OF WASTE PACKAGE DETERIORATION DURING STORAGE

Past experience has revealed deterioration of some waste packages after a certain period of storage. In recent years, the possible mechanisms of package degradation have been well explored and are sufficiently known to be minimized or completely avoided by qualified conditioning and proper design of the waste storage facility. The examples of deterioration of waste packages and the possible mechanisms of deterioration described below are not exhaustive but they illustrate the importance of quality of waste packages and storage conditions to ensure safe storage.

5.3.1. Waste containers

Failure of waste packages during interim storage may occur owing to hidden defects in the waste container manufacture, or unknown mechanisms of the interaction of the waste container with the waste form, i.e. failures within the quality assurance programme. In practice, these undetected defects may cause deformation of the waste package during handling, loading, storage and retrieval. Container defects tend to manifest themselves early, and this is a good reason to segregate waste by the date of conditioning. In this way, systematic problems with container integrity can be avoided.

5.3.2. Gas generation

Any radioactive waste type, but especially alpha bearing waste, waste containing hydrocarbons, and biological waste that has not been adequately treated, will generate gases. In some cases these gases are flammable (e.g. hydrogen) and may pose the risk of fire or explosion. At the least, they will pressurize the waste package and could deform it, making the package unacceptable for interim storage. To prevent this occurrence with wastes that generate hydrogen, vent devices can be installed on the drum which automatically vent gases in one direction when a certain pressure is exceeded. When penetration of the package, needed to install this device, is not permitted or not advisable, hydrogen recombiners can be inserted in the waste matrix to prevent gas formation. In other cases non-airtight cover lids are applied on the waste drums (Eurostorage at the Belgoprocess site) to prevent overpressure in those packages. In this case, the storage area should have a moderate ventilation system to avoid accumulation of hydrogen.

5.3.3. Physical and chemical changes

Some waste forms, although immobilized to meet waste acceptance criteria, change their properties in the container over time for a variety of reasons, including phase separation, incomplete reaction of contents during treatment and immobilization, radiation effects and extremes in storage conditions. Common problems observed in waste forms include: expansion of the waste form (bitumen) followed by failure of the waste container, generation of liquid in the waste package and corrosion and failure of the container and disintegration of the waste form, with subsequent creation of void spaces in the package.

5.3.4. Change in radiation dose rate

As a consequence of some processes, a change (increase) in dose rate at the surface of the waste package can occur. The increase may be due either to migration of radionuclides within the waste package and their concentration in a certain part of the package or to failure of the shielding capability of the container. This situation may indicate a significant problem with the waste package as a whole. In that case, the waste package should be retrieved from the storage facility, examined, and reconditioned if necessary. If the change in dose rate is acceptable from a radiation protection standpoint, and if the dose rate does not exceed the limits established for the facility, the waste package may remain in the store after verification of the container's integrity.

5.3.5. Accelerated deterioration due to mechanical damage

Handling and placement of a waste package in a storage facility using equipment not specially designed to prevent mechanical damage have frequently resulted in deterioration of the waste container. The damage ranged from paint scratches which accelerated corrosion of the container material to destruction of the container, which subsequently led to the failure of the waste form containment, resulting in surface radioactive contamination of the package itself as well as of adjacent packages.

5.3.6. Accelerated deterioration due to package corrosion

Storage of waste packed in mild steel containers in an open environment has led to massive package failure from exposure to environmental elements. This has also occurred to a much lesser extent in unheated engineered stores. Corrosion of the container wall due to free liquor within the package has also been experienced.

5.3.7. Galvanic reaction

Carbon steel and other metal containers can deterorate owing to galvanic reaction (a difference in electrical potential that results in an induced electrical current) when the drums come into contact with unpainted surfaces of other metals. The longer the waste is stored, internal or external influences can make package failure more likely. After a certain time, however, the probability of package failure for most types of waste becomes limited to external factors only.

5.4. STORAGE FACILITIES IN SELECTED MEMBER STATES

The Appendix provides a list of current, worldwide storage facilities, as presented at the Technical Committee Meeting in Vienna in September 1996. Various storage facilities associated with private sector industry, e.g. nuclear power plants, are located throughout the USA, and are too numerous to mention in this report.

6. WASTE PACKAGE MANAGEMENT OPTIONS AFTER THE LICENSED STORAGE PERIOD

6.1. GENERAL MANAGEMENT OPTIONS

The storage period of a waste package depends on many factors: the licensing period of the facility, the physical integrity of the package, economic considerations, and the availability of a disposal facility (either near surface or deep geological) or a reconditioning facility.

After termination of interim storage, there are several possibilities for waste package management. In the most common situation, the packages will be retrieved from storage for transport to the disposal facility. To be accepted in the disposal facility they will need a certification file. In order to establish this file and to demonstrate the acceptability of a package for transport and disposal, inspections must be performed by non-destructive methods as far as possible. In the case of a damaged package, both non-destructive and destructive methods may be used during inspection. The damage will be corrected and the package will eventually be reconditioned in order to be accepted in the final repository.

In other cases, the packages retrieved from the storage facility may be reconditioned in order to comply with transport regulations and waste disposal acceptance requirements (e.g. non-immobilized wastes). Special precautions, including use of an overpack, should be taken to ensure safety during transport to the reconditioning facility if the facility is away from the store.

Finally, waste packages may be retrieved after a decay period when they have become very low level waste or cleared waste. In a few countries, clearance levels have been defined to allow consideration of the packages as cleared waste [15].

In some cases, the non-availability of a disposal facility or the optimization of waste management may lead to prolonged storage of waste packages. When a storage facility is adapted to several different types of package, this will often result in an extension of the licence of the facility. To obtain authorization for prolonged storage of packages, a new safety assessment may have to be made. To this end, a certain number of packages must be inspected in order to verify their integrity during the previous period of storage and to validate facility performance. A failed package has to be reconditioned properly for further safe storage. Methods of verifying waste package contents, container integrity, package stability, and suitability for disposal under the various conditions and cases in which waste can be retrieved are discussed below.

6.2. SURVEY, INSPECTION AND TESTING

6.2.1. Necessity for survey, inspection and testing

The waste packages retrieved from the interim storage facility for disposal must comply with the specified waste disposal acceptance criteria. These are derived from a detailed safety assessment for both the store and the two phases of the repository (operational and post-operational) as introduced in Section 2.2. A typical set of properties of the waste packages which may be quantitatively fixed by WAC for disposal is described in detail in Ref. [16]. These properties are to be controlled by an inspection and testing programme, described below.

The survey, inspection and testing programme must be specifically tailored to those packages retrieved from the storage facility whose integrity is unknown or suspect. For example, where 200 L drums (and other packages) have been stored in excess of 20 years, special provisions should be made to ensure physical and radiological protection of personnel prior to excavation of these packages from unmonitored subsurface storage, because the integrity of these waste packages is unknown. A reliable system of safe retrieval can only be developed in such a case after careful planning and the initiation of a retrieval programme.

Where survey, inspection and testing of conditioned packages retrieved from storage whose characteristics are known and documented are involved, even if the waste packages are surveyed during storage, degraded packages may remain undetected until retrieval. However, the implementation of a proper quality assurance programme during conditioning and storage should lead to a very low probability of waste package failure. In this case the presence of a failed package will be considered extremely unlikely. Therefore efforts should be made to apply the ‘first in – first out’ principle, and initial radiological surveys should be carried out to detect failed waste packages and other situations that increase the risk to personnel safety.

6.2.2. Records review and survey of packages

The inspections normally begin with the review of the waste package records maintained by the storage facility. The waste package records need to be retrieved and reviewed to determine the age of the package, length of time in storage, waste form, container type, unique retrieval requirements and potential package problems. Waste package quality control can be performed by examination of the waste package documentation, which describes the relevant properties of the waste package, and by non-destructive or destructive testing of the waste package itself, when necessary. The decision on which of these procedures would be most suitable for package retrieval is influenced by questions like:

- How complete is the documentation?
- How reliable is the documentation?
- What is the presumed risk potential of the waste package failure?
- What is the obvious state of the waste package?

Quality control by examination of the documentation is simplified when the waste packages to be inspected have been conditioned by a qualified process.

In some Member States, thousands of 200 L drums with operational LLW from nuclear power plants have been checked since 1990 before being disposed of in final repositories. Only a small number were controlled by testing waste packages, while the greater part were controlled by examination of the documentation. As a result, some packages required certain additional conditioning (see Section 6.3.2) prior to disposal, and only a very few were completely withdrawn. The implementation of quality assurance procedures and development of conditioning technologies normally lead to reducing the proportion of failed packages to nearly zero.

When investigation of the records is complete, an initial survey should be performed. It may include a radiological survey to ascertain whether any risk exists from failed waste packages and visual survey of the waste packages prior to immediate retrieval in order to look for signs of pressurization, corrosion, catastrophic package failure and other conditions detrimental to acceptance for further interim storage or final disposal.

The conditions necessary to certify the retrieved packages for further interim storage or disposal should then be defined. These conditions may range from none to repackaging or complete reconditioning, depending on the status of the package and the length of interim storage. Packages that meet the criteria set for the records search, the initial survey, and the visual inspection may be subject to testing to determine whether the WAC of the continued interim storage or the disposal facility have been maintained over the storage life of the package. Whether or not, and to what extent waste packages must be further tested, has to be decided taking into account the content of the records and the state of the packages.

It should also be noted that testing of waste packages is inevitably combined with a dose commitment to personnel. According to the ALARA principle, testing of waste packages must be balanced against the additional knowledge benefit to be gained and must be minimized to a reasonable level.

Testing of the packages may be destructive or non-destructive. If testing is needed, non-destructive rather than destructive tests should be implemented whenever appropriate. Destructive examination of packages is usually limited to a small fraction of the total waste packages retrieved, unless sampling shows that widespread degradation is present. In that case entire lots of waste packages may be identified for repackaging. Non-destructive testing can ascertain many other waste package characteristics, and is performed on a larger number of packages received for disposal owing to its non-invasive nature. Non-destructive and destructive testing methods for waste forms and packages are described in detail in Ref. [16].

6.2.3. Non-destructive testing methods

Non-destructive methods for testing waste packages include all tests that can be conducted without penetrating or opening the waste container. Various techniques have been developed and implemented in Member States, for example:

- Intensive visual inspection to detect corrosion, mechanical damage, penetrations and internal overpressure;
- Weighing to identify heavy parts, e.g. shielding material;
- Dose rate measurements;
- Radiography to determine contents of packages, void spaces, container wall thickness, presence of liquids, etc.;
- Scanning to measure the spacial distribution of gamma radiation and identify prominent gamma emitters;
- Tomography (with an external gamma source or with an accelerator) to detect any inhomogeneity in density;
- Passive and active neutron counting to detect fissile material.

Some of these tests are related to the package integrity control; others give information on the content of the waste package and its distribution. Figure 29 shows a scanner to identify gamma emitting radionuclides in 200 L drums.

In general, non-destructive methods have proved helpful in identifying irregular contents of radioactive waste packages. For major inhomogeneities, however, they may provide qualitative rather than quantitative results. Moreover, alpha emitting nuclides and small amounts of low energy radiation may not be detected. In such cases, destructive methods can supply additional information.

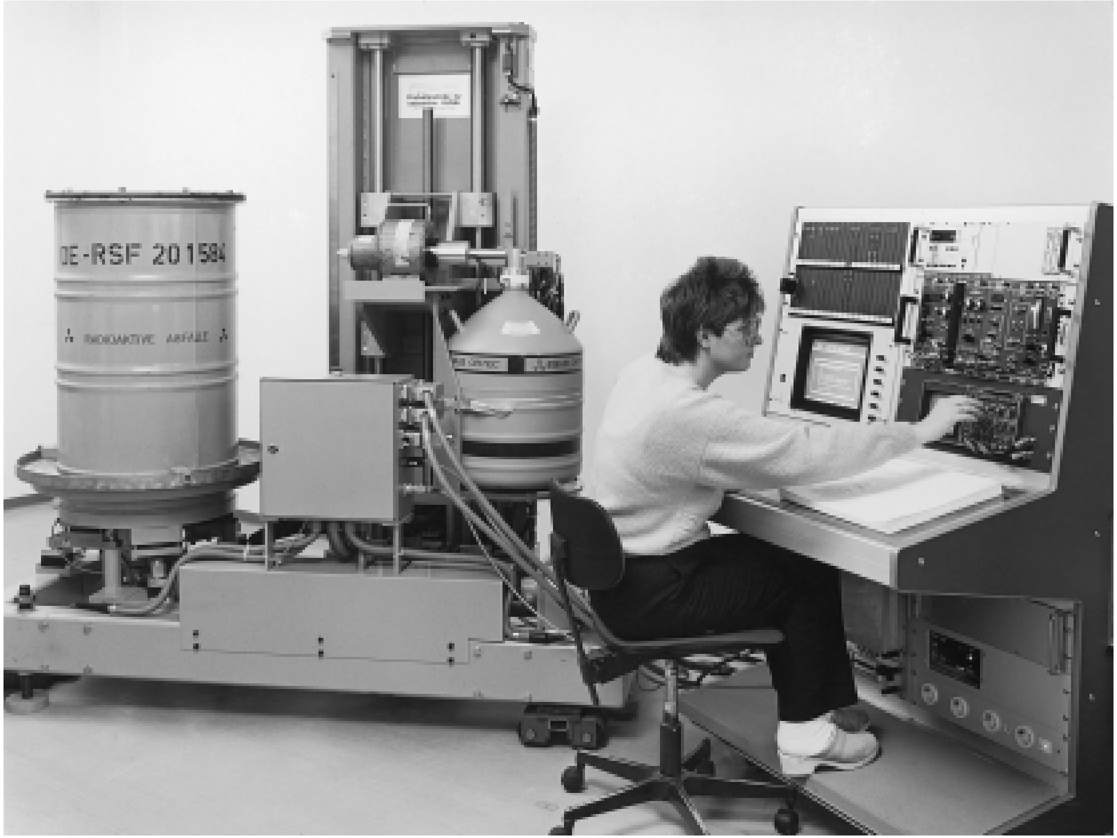

FIG. 29. Gamma scanner for inspection of 200 L drums (Germany).

6.2.4. Destructive testing methods

Destructive methods generally imply taking samples out of the waste packages. Several techniques for sampling LILW packages have been developed and partially implemented in Member States. Sampling of HLW glass is not practised; it is not recommended because of the high activity of the glass, difficulties in sampling and high dose commitment.

Gas samples can be taken by means of a hypodermic needle through the flexible gasket of the waste package, or by a sealed puncture technique through the canister wall. The samples may be analysed for radioactive (e.g. ^{14}C, ^{85}Kr, ^{129}I) and non-radioactive (e.g. hydrogen, hydrocarbons) gases.

Solid samples can be taken by drilling through the container wall or directly into the waste form when the container has been opened. Normal drilling techniques will provide dust that can be analysed, whereas core drilling techniques will provide additional information about the spatial distribution of waste constituents. In the case of a drilling box for taking samples from a 200 L low level waste package, the drilling compartment is ventilated and the exhaust air filtered and checked for radioactivity.

Destructive examination of contents of the waste packages could be done via total separation of the waste form from the container. Void spaces can be checked as well as physical form and the presence of prohibited materials in the waste. It can determine the existence of pyrophorics, water, explosives and other compounds that prohibit emplacement at the disposal site. Samples may also be analysed to identify radionuclides in the waste packages and to establish that the total activity is within the limits of certification.

Mechanical strength of the waste packages may also be checked by crushing. The tested packages in this case require overpacking prior to disposal.

6.3. ACTIONS REQUIRED AFTER THE LICENSED STORAGE PERIOD

6.3.1. Certification for transport and disposal

After retrieval and inspection of the waste package properties relevant to final disposal by either examination of records and documents or testing, it must be determined whether the waste package meets the transport regulations and waste disposal acceptance criteria. Conformity of the waste package with transport regulations and disposal acceptance criteria has to be certified by the transport authority and repository operators, respectively, or by independent experts authorized by the regulatory authorities, or by the legal authorities themselves. The transport organization and the operator of the repository will accept certified waste packages only.

It is essential that non-immobilized waste retrieved from a storage facility is subject to the certification process because such waste must be conditioned and repacked for transport and disposal. The objective is to meet the transport regulations and WAC of the disposal facility. The original waste container may be reused, or it may be crushed and placed with others in an overpack. As the waste undergoes the various processes necessary for certification (summarized in Section 2), a certification document should be developed which follows the waste to its completion as a waste package. A suitable identifier should be provided as required, and the package should be either sent to the disposal facility or returned to the storage facility as a certified waste package.

Characterized and/or conditioned waste generally requires less effort to certify, and involves a lower risk to the operational staff. The possibility of encountering a failed or non-conforming waste package increases with the length of time the package has been in storage. The certification process is usually well under way, and certification for disposal usually involves verification of the transport and disposal WAC against the package condition. Safety assessment takes into account the quality of materials, the quality of the manufacturing process and the length of storage time to estimate the potential of failure or non-conformity of a waste package. If the duration of storage overpasses the licensed period, it may be recommended to reassess this potential for failure.

So far, the experience of certification of LILW for disposal exists mainly in countries that are operating near surface repositories. The waste packages have been designed to comply with the WAC of the existing disposal facility, and obviously they are expected to comply with them during and after the storage period. No worldwide experience exists yet for HLW, but safety assessments of deep geological repositories are being made.

6.3.2. Reconditioning of waste packages

Reconditioning may also be necessary for non-conforming packages, except for those containing non-immobilized waste that is retrieved specifically for reconditioning.

Waste packages may be identified as non-conforming with regard to disposal WAC for several reasons, including incomplete documentation or inadequate information. More complicated problems related to conditioning may also exist, and these problems include: corrosion or mechanically induced damage, gas release, content of free liquids, presence of void spaces, excessive surface dose or radionuclide content. It is important that the record file for non-conforming waste packages is well documented and correctly updated. Excessive amounts of non-conforming waste packages should be avoided; their number should stay within the statistical confidence level so long as a proper quality assurance programme has been established and implemented, and provided that the waste packages are produced in accordance with the waste specifications.

Damaged waste packages may be identified during routine store inspections or at a final retrieval stage. Failure of the waste container due to mechanical damage may be major or minor in nature. Minor dents, scratches, rust or corrosion that are the result of external impacts or other influences may be repaired so long as the package integrity has not been compromised. Major package failures or deformation due to external forces would require reconditioning or use of an overpack.

Failure or non-conformance of the waste form is a larger problem. Should inspection reveal that liquid has been generated in the waste package, or that organics are present, the preferred option from the standpoint of cost and the ALARA rinciple is in situ package remediation. A number of techniques are available to drain fluids through container penetration, e.g. by adding flocculants, absorbents and anticorrosive agents, or simply filling void spaces. Drum venting devices or gas recombiners can also be installed to avoid gas generation problems. Corrosion induced gas production may also be reduced by drying opened waste packages. If the package is deformed from the effects of gas pressurization, or if chemical changes in the package have damaged the waste container, then repackaging or overpacking will be necessary to meet the ongoing storage, transport or disposal waste acceptance requirements.

Corrective action on retrieved non-conforming waste packages might lead to a deviating package dimension and form, caused by overpacking. It might even lead to a change in waste category. In such cases several measures have been developed and implemented in some Member States that will convert such waste packages into a form suitable for final disposal. In Germany, for example, open waste packages are dried in order to reduce the free liquid content as well as the speed of corrosion. The production of hydrogen from corrosion will also be minimized. Figure 30 shows, as an example, the PETRA facility for drying humid packages containing supercompacted waste with a capacity of 1000 drums per year.

Overpacks may mitigate problems in connection with mechanical or corrosion induced effects. In addition, the surface dose levels may be reduced to acceptable levels. Various types of overpack are currently in use. As an example, 200 L drums containing LILW can be inserted into either 400 L drums or a large rectangular container manufactured of steel or reinforced concrete. The open space in these overpacks may be grouted with cement to increase the mechanical and shielding properties.

6.3.3. Retrieval for disposal as very low radioactive waste or cleared waste

Long term storage may allow some low activity or short lived waste packages to decay below clearance levels established by regulatory authorities. In this case

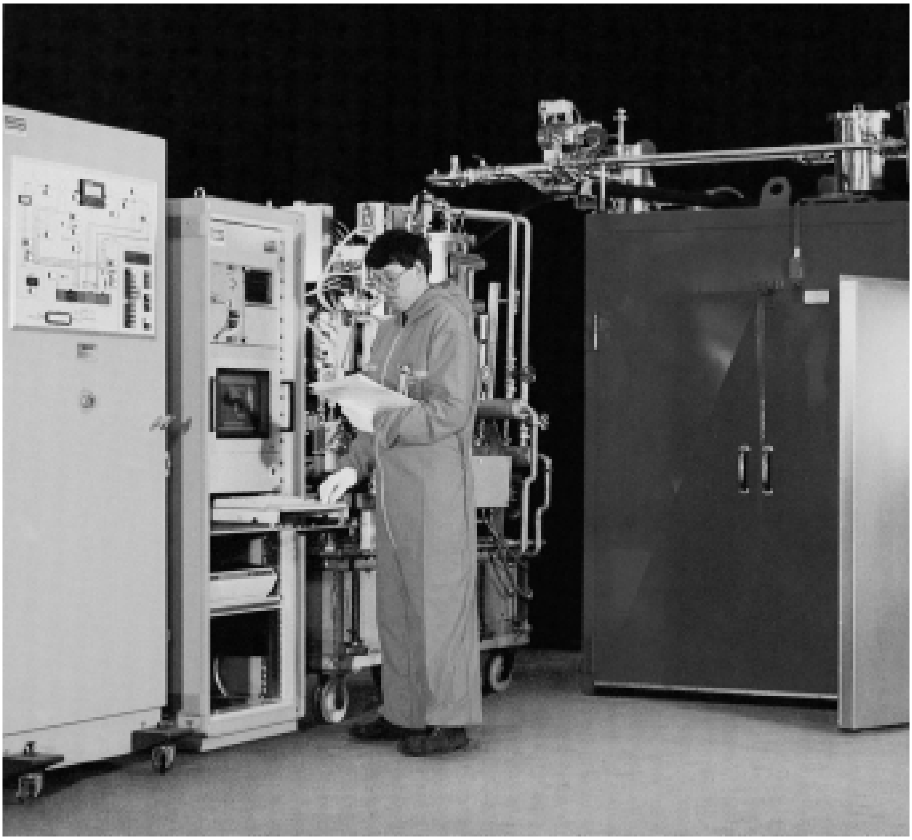

FIG. 30. PETRA facility for drying waste drums (Germany).

prolonged storage is a benefit, because it results in a certified waste package that may be disposed of in a relatively inexpensive waste disposal facility or recycled to industry. It is essential to manifest all of this waste very carefully when the waste package is characterized in order to demonstrate that the initial levels were correct and this material is therefore no longer regarded as radioactive.

Waste that may be subject to clearance should be segregated and, if a large backlog of waste exists, this waste should preferentially be left in storage. The controls at retrieval must be commensurate with future utilization (no reuse of the installation, no reuse of the decayed waste) and take into account the related conventional hazardous risks. For example, chemical toxicity will play an important role in the case of disposal at industrial waste disposal sites.

The legal framework for this type of waste depends on the country. It should be noted that Member States have not adopted a consensus position in this regard.

6.3.4. Prolonged storage

It may happen that waste packages cannot be brought into conformity with the WAC of a certain repository, or that a repository is not yet available at the time when the design life of the interim storage facility runs out or the storage licence expires. For these or some other reasons the need for prolonged storage may arise.

In general, prolonged storage may be considered as storage of waste in a facility beyond the time originally planned by the design and licence. For LILW, at least a ten year period has been recommended in the design capacity of storage facilities in developing countries without current disposal capacity [17, 18]. Of course, the absolute capacity of the storage facility that will hold ten years' worth of waste will vary among Member States. In addition, the design life of this storage facility will usually greatly exceed ten years (30 to 50 years is typical). A period exceeding ten years was considered appropriate for a waste package because it was established that problems with the packages would begin to manifest themselves within that period of time, and special provisions for continued storage of the waste would be required. This may, however, not be appropriate for waste packages designed and licensed for long term storage, e.g. heavy shielded casks for HLW and spent fuel storage. It may also not be appropriate for packages in modern stores, conditioned to rigorous standards under a quality assurance programme.

To authorize prolonged storage, a new safety assessment of the storage facility is necessary. Packages should undergo representative sampling, and if all the packages are not accessible, restacking must be assessed. Packages must be inspected to a certain extent, first by visual inspection, and then by some other testing methods if necessary.

It is recognized that Member States with a large backlog of waste in prolonged storage will commit significant resources to comply with this requirement. However, Member States with small quantities of conditioned waste may benefit from prolonged storage, especially when the construction of a disposal facility has been delayed to the distant future.

7. RECOMMENDED MEASURES TO ENSURE OPTIMAL PERFORMANCE OF WASTE PACKAGES DURING STORAGE

A series of measures to ensure optimal package performance under conditions of storage has been developed and should serve as recommendations to Member States, with explanation of their applicability. The need to establish waste acceptance criteria for storage, transport and disposal, and to comply with them at the point of waste generation, results in the practices described below. The implementation of such practices and qualification of the conditioning process will result in a package readily acceptable for storage, transport and disposal.

7.1. WASTE GENERATION AND CHARACTERIZATION

(a) Generated waste should be segregated as far as possible to facilitate subsequent treatment and conditioning in order to to reduce waste toxicity, mobility and volume. Member States should take into account their present and planned national waste management systems in the generation of radioactive waste. If no disposal facility is available in the foreseeable future, the storage period of waste packages will probably have to be prolonged, and provisions for this situation must be planned well in advance.

(b) Waste characterization and implementation of an adequate quality assurance programme should begin at the point of waste generation by establishing a file containing detailed information on the waste.

7.2. STORAGE FACILITIES

(a) It is recommended that interim storage facilities should not accept any new waste that is not adequately characterized. Every package must comply with the acceptance requirements of the storage facility.

(b) Non-immobilized wastes emplaced in containers for storage should be segregated in the storage facility to the extent practical. The packages should also be segregated by waste type and storage duration.

(c) Facilities for the storage of waste should have a design life that is independent of the emplaced packages. The safety assessment should support the suitability of the facility for the duration of its intended use.

(d) Storage of low contact dose rate LILW should allow for visual inspection of packages. For prolonged storage it should be recognized that surveillance requirements may need to be modified during the period of storage. For the storage of high contact dose rate LILW, HLW and spent fuel, indirect controls may be put in place to inform the operators in the event of a failure.

(e) If the waste is characterized and conditioned properly within an adequate quality assurance programme, failure of the package is not expected. But in the event of package failure, for any reason, provisions for retrieval of a package must exist in the storage facility.

(f) Packages might be damaged if they fall during handling in a storage facility, and in that case the storage facility must provide for retrieval of the package as well as decontamination of the area, if necessary. If a package failure occurs during storage owing to the waste form or a widespread external corrosion of the container, then further action to eliminate the hazard for all packages of the same type should be evaluated. Packages that fail during storage and cannot be retrieved and remediated should be isolated in place, whenever possible, to protect personnel, the environment and neighbouring waste packages from contamination.

7.3. PROVISION FOR RETRIEVAL OF WASTE PACKAGES

(a) Waste retrieval should be carefully planned and, as far as practical, preceded by a detailed survey and inspection of the waste packages to be retrieved. Retrieval activities should follow a careful review of the manifest of all waste in storage. The sequence of retrieval of waste packages should take safety aspects into account, including the condition of the packages. It is recommended that in some cases high dose rate or other hazardous waste be given priority for attention. Each package in the interim storage facility should be registered and all records kept up to date.
(b) Conditioning of retrieved waste in order to correct package problems should focus on cost effective remedies for non-conforming packages. In situ remediation of these packages should be given priority. Packages with serious container structural problems must always be overpacked.

8. CONCLUSIONS

Both conditioning and storage of radioactive waste are fundamental steps in the radioactive waste management process to ensure protection of the population and the environment. If the safety principles and recommendations presented in this report are applied, then the interim storage of packages can be considered safe. The expected evolution of the packages is limited to the decrease of activity and thermal power.

Throughout the process of storage the recommended measures, taken together, demonstrate ALARA principles and involve the lowest life cycle cost. However, they demand rigorous planning on the part of the national organizations charged with implementing the waste management system. Decisions regarding waste storage should not be deferred as part of the larger issue of waste management. If interim storage is selected in favour of disposal by design or default, the same level of forethought and planning must drive the storage facility as if it were to be a facility for final disposal of waste. Equally, where justified on safety grounds, on-site management of radioactive waste should not be unduly constrained by the possible requirements for final disposal.

Appendix

STORAGE FACILITIES IN SELECTED MEMBER STATES

Country/location (Name of facility)	Type of storage	Type of building	Category of waste	Type of package[a]
Argentina	Engineered	Warehouse	Cemented LILW	200 L, 400 L drums
Austria	Engineered	Warehouse	Cemented LILW	200 L drums
Belgium/Mol/Dessel	Engineered	Warehouse	LILW, low contact dose rate	28 L cans, 200 L drums
Belgium/Olen	Area	–	^{226}Ra contaminated LL ore waste	– –
Belgium/Mol	Area	–	LILW, low contact dose rate, NIW, combustible	1 m^3 SS container
Belgium/Mol	Engineered	Shelf piling	LILW, liquid NIW	30 L PE bottles
Belgium/Mol	Engineered	Concrete floor with sand walls and roof, underground steel tubes	LILW, high contact dose rate. HLW, non-immobilized	30 L MS boxes, SS 60 L boxes, PE boxes
Belgium/Mol/Dessel	Engineered	Warehouse (25 cm concrete thickness)	LILW, bitumen, haematite, concrete, polystyrene	200 L, 400 L, 600 L MS drums, 665 L asbestos/cement containers, 600 L, 1000 L, 1500 L concrete containers
Belgium/Dessel	Engineered	Heavily shielded concrete cells (1.7 m wall thickness)	HLW glass (Cogema waste)	150 L SS canisters

Capacity	Package handling	Package stacking	Engineered features	Design life (years)	Provisions for inspection	Operating since
7000 m^3	Overhead bridge crane	Horizontal	Forced ventilation	–	Yes	–
3000 m^3	Lift truck	Up to 5 layers	Natural ventilation	<20	No	1982
4500 m^3	Lift truck	Up to 5 layers	–	<20	No	1990
–	–	–	–	–	–	–
500 m^3	Lift truck	Up to 3 layers	–	–	–	1989
120 m^3	Manual	1 layer per shelf or 4 layers	Ventilation for α waste	<10	Yes	1990
–	Shielded lift truck	Up to 2 layers	Natural ventilation, floor drains	<20	No	1990
17 300 m^3 (43 445 packages)	Overhead bridge, shielded truck	Up to 6 layers	Natural ventilation	<20	Yes	1986
90 m^3 (600 containers)	Overhead bridge, shielded truck	Up to 10 layers	Forced ventilation	50	Limited	1997

Country/location (Name of facility)	Type of storage	Type of building	Category of waste	Type of package[a]
Belgium/Dessel	Engineered	Concrete bunkers (80 cm wall thickness)	LILW, high contact dose rate, cemented hulls and end fitting pieces, bituminized sludges from Cogema	1200 L asbestos/ cement containers, 200 L SS drums
Belgium/Dessel	Engineered	Concrete bunkers (80 cm wall thickness)	LILW, high contact dose rate, immobilized in bitumen, concrete, asbestos/cement	700 L asbestos/ cement containers, 200 L SS drums, 200 L MSG drums, 400 L painted drums
Egypt/Inshas	Engineered	Modular concept	LILW cemented	Concrete canisters
France/La Hague (R7)	Engineered	Heavily shielded concrete vaults (5 vaults)	HLW glass	150 L SS canisters
France/La Hague (EDS)	Engineered	6 cells	Cemented hulls and end fittings, technological waste	1200 L SS containers, asbestos/cement containers, fibre concrete containers
France/La Hague (extension of EDS facility – D/E EDS)	Engineered	Modular concept (2 cells planned)	Technological waste, compacted hulls and end fittings	150 L SS canisters
France/La Hague (extension of glass storage facility – E/EV South East)	Engineered	Modular concept, heavily shielded concrete vaults (2 vaults built)	HLW glass	150 L SS canisters
France/La Hague (T7)	Engineered	Heavily shielded concrete vaults (4 vaults)	HLW glass	150 L SS canisters

Capacity	Package handling	Package stacking	Engineered features	Design life (years)	Provisions for inspection	Operating since
732 m^3 (270 containers and 2042 drums)	Overhead bridge, remote operated trolley	Up to 4 layers	Forced ventilation	<50	Limited	1997
4556 m^3 (18 393 drums)	Overhead bridge, remote operated trolley	Up to 4 layers	Forced ventilation, filtration of exhausted air, water control in pits	<50	Limited	1978
–	Overhead bridge crane	2 layers	Natural ventilation	>30	Available	1997
4500 canisters	Loading/ unloading machine	9 canisters per pit	Forced ventilation	<50	Limited	1989
2484 drums, 1184 containers, 4400 containers	Overhead bridge crane.	3 layers vertical, 8 layers horizontal, 8 layers horizontal	Forced ventilation	–	Limited	1990
20 000 canisters	Overhead bridge crane	4 layers	Forced ventilation	<50	Limited	2000 (planned)
4320 canisters	Loading/ unloading machine	12 containers per pit	Natural convection, forced ventilation	<50	Limited	1996
3600 containers	Loading/ unloading machine	9 containers per pit	Forced ventilation	<50	Limited	1992

Country/location (Name of facility)	Type of storage	Type of building	Category of waste	Type of package[a]
France/Marcoule (CEA)	Engineered	1 vault	HLW glass	100 L SS canisters
France/Marcoule (Cogema)	Engineered	Heavily shielded concrete vaults	HLW glass	150 L SS canisters
France/La Hague (STE3)	Engineered	Warehouse	Bituminized waste	200 L drums
France/La Hague (D/EE6)	Engineered	Warehouse	Bituminized waste	200 L drums
Germany/Gorleben	Engineered	Warehouse	HLW spent fuel	Storage/ transport casks (CASTOR)
Germany/Ahaus	Engineered	Warehouse	Spent fuel	Storage/ transport casks (CASTOR)
Germany/Greifswald (ZLN)	Engineered	Warehouse	LILW	Containers, drums
Germany/FZK Karlsruhe	Engineered	Warehouse	LILW	Containers, drums
Germany/FZJ Jülich	Engineered	Warehouse	Spent fuel, LILW	CASTOR casks, drums
Germany/Mitterteich	Engineered	Warehouse	LILW	Drums, containers

Capacity	Package handling	Package stacking	Engineered features	Design life (years)	Provisions for inspection	Operating since
–	Overhead bridge, loading machine, trolley	8 layers	Forced ventilation	30	Limited	1971
2200 canisters	–	10 containers per pit	Forced ventilation	<50	Limited	1978
20 000 drums	Overhead crane	4 layers	Ventilation	–	–	–
36 000 drums	Overhead crane	4 layers	Ventilation	–	–	–
400 casks	Overhead bridge crane	No stacking	Natural convection	50	Visual inspections, monitoring leaktightness of casks	1983
420 casks	Overhead bridge crane	2 layers	Natural convection	50	Monitoring leaktightness, visual inspections	1983
200 000 m^3	Overhead bridge crane	–	Natural convection	50	Visual inspections	1997
–	Overhead bridge crane	–	Natural convection	50	Visual inspections	1980
–	Overhead bridge crane	2 layers	Natural convection	50	Monitoring leaktightness, visual inspections	1978
1500 drums and containers	Overhead bridge crane, loading machine	Up to 5 layers	Natural convection	50	Visual inspections	1986

Country/location (Name of facility)	Type of storage	Type of building	Category of waste	Type of package[a]
Germany/Gorleben	Engineered	Warehouse	LILW	Drums, containers
Germany/Gorleben	Engineered	Warehouse	Spent fuel, HLW glass	Transport and storage casks
India/Trombay	Engineered	Trenches	HLW glass	MS and SS drums
India/Tarapur	Engineered	Tile holes	HLW glass	SS canisters
India/Kalpakkam	Engineered	Heavily shielded concrete vaults	HLW glass	SS canisters
Korea, Republic of	Engineered	Warehouse	LILW	MS drums, concrete lined MS drums
Netherlands/ Vlissingen	Engineered	Warehouse	LILW, low contact dose rate	200 L, 1000 L containers
Slovakia/ Jaslovske Bohunice	Engineered	Warehouse	LILW	200 L, 100 L MS drums
Slovakia/ Jaslovske Bohunice	Engineered	Shielded concrete vaults (4) with channels	Vitrified LILW, high contact dose rate	SS canisters
Sweden (OKG)	Engineered	Underground interim store	LILW	Concrete and steel containers
Sweden (Ringhals)	Engineered	Warehouse with concrete walls (2 buildings)	LILW	Concrete containers and steam generators without shielding
Sweden/Barsebäck	Engineered	Warehouse with concrete walls	LILW	–

Capacity	Package handling	Package stacking	Engineered features	Design life (years)	Provisions for inspection	Operating since
15 000 m^3	Loading machine	Up to 4 layers	Natural convection	50	Visual inspections	1983
420 casks	Overhead bridge crane	–	Natural convection	50	Monitoring leaktightness, visual inspections	1983
–	Fork lift	Up to 3 layers	–	100	Monitoring by borewells	1961
–	Crane	–	Forced ventilation		Removable top plug	1972
–	Crane	–	Forced ventilation		Periodic physical inspections	1983
–	Lift truck	3 layers	Concrete shielding walls	–	–	–
24 000 m^3 or 50 000 containers	Fork lift truck	9 or 4 layers	Natural ventilation	100	Humidity, temperature monitoring	1992
4600 drums	Shielded lift truck	2 layers	Natural ventilation	–	Limited	1988
296 canisters	Overhead crane, shielded transport (internal) and loading device	2 canisters per channel	Natural or forced ventilation	(Tens of years)	Limited	1996
14 000 m^3	Overhead crane	–	Forced ventilation	50	Every 5 years	1980
17 000 m^3	Overhead crane	–	Forced ventilation	50	–	I–1975, II-1980
20 000 m^3	Overhead crane	–	Forced ventilation	50	–	1981

Country/location (Name of facility)	Type of storage	Type of building	Category of waste	Type of package[a]
Sweden/Studsvik	Engineered	Underground interim storage	LILW	200 L drums, concrete and MS containers
Sweden (CLAB)	Engineered	Underground interim storage with 4 water pools	LILW, spent fuel mainly	SS baskets
Switzerland/ Würenlingen	Engineered	Warehouse	LILW up to surface rate 2 mSv/h	MS drums, concrete containers
UK/Sellafield	Engineered	Shielded concrete vaults (3 stores)	LILW, high dose rate, encapsulated hulls and sludges	500 L SS drums
UK/Sellafield	Engineered	Heavy shielded vault	HLW glass	150 L SS canisters
UK/Sellafield	Engineered	Warehouse (several)	LILW, low contact dose α waste	200 L MS and 500 L SS drums
UK/Sellafield	Engineered	Concrete vault	LILW, high contact dose rate	3 m^3 MS box concrete lined
USA/Hanford[b]	Engineered	Multiple bldg.	LILW, α waste	Drums, boxes
	Subsurface	Retrievable trenches		200 L drums
	Area	Asphalt pad		

[a] SS – stainless steel; MS – mild steel; MSG – mild steel galvanized; PE – polyethylene.

[b] Hanford is an example of DOE sites including Rocky Flats Environmental Technology Site, Idaho National Engineering Laboratory, Los Alamos National Laboratory and Savannah River Site, all of which have several forms of storage for radioactive waste awaiting disposal. Some sites also feature subsurface and area storage.

Capacity	Package handling	Package stacking	Engineered features	Design life (years)	Provisions for inspection	Operating since
20 000 m^3	Overhead crane	–	Forced ventilation	50	Every 5 years	1984
12 000 m^3	Overhead crane	–	Forced ventilation	–	–	1985
2000 m^3	Overhead bridge crane	8 layers	Forced ventilation	> 35	Limited	1992
60 000 drums	Overhead bridge crane	12 stillages, 4 drums per stillage	Building ventilation	50	Visual, on sample retrieved	1990
8000 canisters	Charging machine	10 layers in timble tube	Natural convection	50	No	1990
50 000 drums	Shielded forklift truck	4 layers	Monitored ventilation	50	Yes	1960
1836 boxes	Remotely operated trolley	3 layers	Building ventilation	50	–	1990
40 000 drums as needed	Fork lift	1 or 4 layers	–	20	Regular	1993
	Fork lift		–		None	1970
	Fork lift		–			1993

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